(NASA-CR-120343) SPACE PROCESSING APPLICATIONS PAYLOAD EQUIPMENT STUDY. VOLUME 2B: PAYLOAD INTERFACE ANALYSIS (POWER/THERMAL/ELECTROMAGNETIC (TRW Systems Group) 152 p HC $10.75 CSCL 22B G3/31

N74-34329

Unclas 50123

SPACE PROCESSING APPLICATIONS PAYLOAD EQUIPMENT STUDY

VOL. IIB. PAYLOAD INTERFACE ANALYSIS (POWER/THERMAL/ELECTROMAGNETIC COMPATIBILITY)

DPD NO. 40
DR NO. MA-04
DCN NO. 1-3-21-00235
CONTRACT NO. NAS 8-28938

JULY 1974

R. L. HAMMEL
A. G. SMITH
(EDITORS)

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

BY

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

FOREWORD

Phase II documentation prepared for the Requirements and Concepts for Space Processing Payload Equipment Study under Contract NAS 8-28938 resulted in a three-volume report. These volumes are as follows:

Volume I. Executive Summary
Volume II. Technical
- IIA. Experiment Requirements
- IIB. Payload Interface Analysis
- IIC. Data Acquisition and Process Control
- IID. SPA Kit
- IIE. Commercial Equipment Utility

Volume III. Programmatics and Payload Accommodation

Volume II, Technical, is published as five sub-volumes in order to facilitate presentation of topical groupings of data.

Phase I documentation was previously documented in 1973 as three volumes under the title, Requirements and Concepts for Materials Science and Manufacturing in Space.

One feature of this study has been the close association between the NASA Shuttle Sortie Working Group on Materials Science and Manufacturing in Space and the study contractor, TRW Systems Group. The NASA-MSFC study COR, Mr. Kenneth R. Taylor, has provided TRW Systems Group with working group documentation and, in turn, has coordinated study task results into the activities of the working group.

The TRW Systems Group personnel who assisted in the preparation of Volume IIB are listed below:

Mr. R. D. Stevenson (Power)
Mr. P. R. Mock (Thermal)
Mr. K. W. Biber (EMC)
Mr. R. L. Hammer (Editor)
Ms. A. G. Smith (Editor)

SPACE PROCESSING APPLICATIONS PAYLOAD EQUIPMENT STUDY

VOL. IIB. PAYLOAD INTERFACE ANALYSIS (POWER/THERMAL/ELECTROMAGNETIC COMPATIBILITY)

DPD NO. 40
DR NO. MA-04
DCN NO. 1-3-21-00235
CONTRACT NO. NAS 8-28938

JULY 1974

R. L. HAMMEL
A. G. SMITH
(EDITORS)

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

BY

TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

TABLE OF CONTENTS

TABLE OF CONTENTS (con't)

TABLE OF CONTENTS (Con't)

LIST OF FIGURES

LIST OF FIGURES (con't)

LIST OF TABLES

1. SUMMARY

As a part of the task of performing preliminary engineering analysis of modular payload subelement/host vehicle interfaces, a subsystem interface analysis was performed to establish the integrity of the modular approach to the equipment design and integration. Salient areas that were selected for analysis were power and power conditioning, heat rejection and electromagnetic capability (EMC).

1.1 POWER AND POWER CONDITIONING

Earlier studies indicated that virtually all equipment requires special conditioning of the input power. An examination of the input power available from the Spacelab indicated a possible mismatch in special equipment requirements for a majority of cases (including commercial equipment). It was determined that maximum flexibility in integrating subelements into the Spacelab can be achieved if the power conditioners are not centralized, but are part of the equipment.

The number of possible SPA experiments are diverse. For the purpose of narrowing the scope of this study, the equipment and load profiles for twelve representative experiments were identified. Two of the twelve experiments were chosen as being representative of the group and have been described in greater detail to illustrate the evaluations used in the analysis.

The Shuttle Orbiter will provide electrical power from its three fuel cells in support of the Orbiter and the Spacelab operations. One of the three Shuttle Orbiter fuel cells will be dedicated to the Spacelab electrical power requirements during normal Shuttle operation. This power supplies the Spacelab subsystems and the excess will be available to the payload. The current Spacelab subsystem requirements result in a payload allocation of 4.0 to 4.8 kW average (24 hour/day) and 9.0 kW peak for 15 minutes.

Additional power sources must be provided to fulfill electrical power requirements that exceed the allocation of electrical power from the Orbiter. The power sources considered were supplemental and/or peaking battery kits and the use of a Power-Heat Rejection Kit. This kit will contain up to two Shuttle-type fuel cells and the necessary plumbing,

controls, reactants and tankage to satisfy the SPA experiment requirements. The Power-Heat Rejection Kit would provide up to 14 kW of continuous power and peaks of up to 24 kW for 15 minutes.

The use of the experiment payload allocation from the Orbiter and the Power-Heat Rejection Kit will provide electrical power to the SPA experiments of from 4.0 to 18.8 kW continuously and peaks of up to 33 kW for 15 minutes.

The electrical power conditioning and distribution subsystem must distribute power to the experimental equipment from the power source, in a safe, efficient manner. A number of concepts were considered and compared relative to:

1) Impact on subelement payloads
2) Impact on host vehicle (Spacelab)
3) Modularity/flexibility
4) Efficiency, weight and size
5) Safety
6) Electromagnetic compatibility (EMC)

This comparison resulted in the following recommendations: A 115 V 400 Hz, single-phase system for the low power experiment bus, and a 115 VAC-1600/1800 Hz, 3-phase, 4-wire system for the high power experiment bus. Power conversion from 28 VDC to 400 Hz and 1800 Hz Ac will be accomplished by static DC to AC inverters, which are frequency and phase synchronized to prevent dynamic interactions and system instability. The inverters will be self-protecting for overvoltage on input and overload and short circuit on output. Further consideration should be given to the modularization of both the input and output junction boxes into several separate modules so that in case of a major fault some bus protection will be provided by the physical separation of the switching elements.

Of course, throughout this activity a continuous trade study of power conditioning and distribution equipment efficiencies on the thermal control requirements was made. Several thermal interfaces between the electrical power and thermal control subsystems were evaluated. The primary interface is the dissipation of all electrical energy consumed by the experiments, i.e., the energy under the experiment power source profiles must be dissi-

pated by the thermal control subsystem. The dissipation of this energy requires additional electrical energy for operation of the thermal control equipment resulting in a increase in electrical energy that must be dissipated. Other thermal interfaces considered were the dissipation of heat from the fuel cells and the resultant by-product (water) produced by the fuel cells for potential use by the thermal control subsystem. Based upon the experiment load requirements and assuming the use of the Power-Heat Rejection Kit, a thermal control pump system electrical power requirement of 470 W continuous was determined to satisfy the thermal control subsystem requirements.

1.2 THERMAL PERFORMANCE REQUIREMENTS

The thermal control subsystem will provide the required thermal protection to maintain all subsystems within thermal limits for all mission phases for the experimental equipment. Waste heat dissipation timelines were developed for the equipment selected in the subelements. The timelines were necessary to establish magnitude and duration of peak loads. Items of equipment that have waste heat requirements were separated into two groups: (1) those that can be met by the Spacelab capability and (2) those items that require supplemental capability. In addition to the amount of heat, some items of equipment were identified that must meet specific temperature requirements such as component touch or condensation temperature limits.

For the purpose of assessing the magnitude of the thermal control problem, three different thermal control system concepts were investigated to determine their capability to provide the necessary thermal control. Although the assessment was of a preliminary nature, the concept analyses did indicate a number of areas where modifications to SPA timelines and/or equipment would be necessary.

The air cooling system concept depends upon the Spacelab supplied air flow for cooling of rack-mounted electronic equipment. In the analysis of this concept, a simplified thermal model of a typical cabin thermal control system and the SPA air cooling loop were generated. Based on the analyses, it appears that air cooling is feasible providing the necessary P/UA* can be provided on the commercial equipment.

---

*P = Component Power
UA = Effective Thermal Conductance from Component to Coolant

The liquid cooling system is similar to the air cooling concept except that the equipment mounting rails in the rack are cooled by coolant lines. A parametric analysis was conducted to assess the feasibility of suing a water cooling loop with cold plate mounted electronics. The liquid cooling concept's feasibility depends, to a large extent, on the design of the liquid distribution system. A properly designed system must be capable of providing the required flow rate at a low enough pressure drop to result in a reasonable pump power requirement and it appears that a liquid cooling loop would be feasible.

A heat pipe system employed as a cooling concept for Spacelab was also investigated. Such a system would provide the capability of a thermal energy transport without an attendant expenditure of power for an electromotive device (fans, pumps, etc.). It was determined that the heat transport requirements on the heat pipe system that results from a typical rack power dissipation distribution are too severe. The number of pipes required were considered impractical in relation to air or pumped liquid cooling. Heat pipes can be used, however, for dumping heat from the various components into the air ducts.

The Power/Heat Rejection Kit (PHRK) thermal control subsystem (TCS) consists of a pumped liquid loop which rejects thermal energy to space via a thermal radiator located on the exterior of the PHRK structure. The system is a liquid loop using two radiators to reject the thermal energy absorbed from the fuel cells, electronic equipment and furnaces. The primary radiator is a high temperature radiator for high heat rejection and the secondary radiator is to provide temperature drop in approximately ten percent of the flow for cooling room-temperature operating, electronic equipment. A thermal capacitor is included in the system downstream of the primary radiator to store the thermal energy that exceeds radiator capacity until such a time as the thermal load falls within radiator capability.

The heat rejection subsystem was baselined on a 7 ft. body-mounted radiator length. The usable experiment duty cycle was then defined for this system versus the average experiment power involved. Subsequently, study of the heat rejection system designs required to operate at 7 kW and 14 kW electrical steady-state was made. At the fuel cell sources, the

the previous electrical values reflect a steady-state heat rejection problem of 11.3 kW and 22.3 kW, respectively. The steady-state approach to defining the use of a supplemental power and rejection kit represents an extreme usage limit. On the other hand, examination of possible duty cycle usages based upon average experiment power illustrates usage options with this approach. While the SPA experiment activities revolve around both power and energy availabilities, it can be conclusively shown that heat rejection will always pose the primary limitation in achieving the associated subsystem support. This is particularly true in light of the limitations affecting the thermal subsystem design of radiator size, fuel cell temperatures and use of capacitors.

1.3 ELECTROMAGNETIC COMPATIBILITY

A similar activity was performed for the analysis of the electromagnetic compatibility (EMC) interface. Historically, EMC has been approached by testing engineering models per a military specification. In contrast, modeled payload analysis can be used to predict, characterize and provide trade solutions in the design activity. Most of the data required for detailed EMC study was not readily available. A beginning was necessary for two important reasons: One is that the problem area had to be opened up to establish the approach to EMC control; the other was that in order to exploit every mission opportunity, SPA payloads must be capable of operating in close proximity to almost any other experiment. An EMC evaluation of commercial equipment was one of the most important things to emerge from this effort, since commercial equipment of the kind envisioned by SPA had not considered EMC in the broad sense as necessary with space systems. This showed up in component design, component assembly techniques and lack of measured or analytical EMC data. The EMC problem is further aggravated by the high currents and voltages required by SPA. The initial efforts have been aimed at various levels of categorization of the payloads and interfacing equipment and at the establishment of initial estimates for the EMC environment for the representative payload configurations. A test program was performed to measure some of the pertinent EMC characteristics of R&D prototypes of equipment similar to that under consideration as potential SPA payloads.

2. INTRODUCTION

2.1 OBJECTIVES

In keeping with the direction initiated by past studies defining SPA payload equipment concepts as modular, reconfigurable and reusable groupings of apparatus, this task has attempted to perform a systems design analysis on the major equipment items. The equipment items have been categorized into groupings. Particular attention was given to groupings that support a number of projected experimenters involved in multi-mission, shuttle-implemented, space processing activities.

Aligned with maintaining a consistent flow of information that would determine the feasibility of apparatus, alternatives and accommodation concepts, present study activities selected representative categories for the expressed purpose of reducing the myriad of variability in equipment redundancy. The study activities included further analyses of space processing considerations in relation to three major subsystem interfaces: electric power, thermal and electromagnetic compatibility (EMC).

The major direction and scope of this task's efforts can be summarized in a relatively simplistic manner -- attain sufficient data that can be parameterized. To perform a series of tradeoff studies that would relate SPA payload requirements to Spacelab/Shuttle capabilities, it is necessary to evaluate a number of physical interfaces. The compilation of these equipment/experiment performance and requirement parameters are the basic substance of this analysis. The product of this study should then be considered as a project management tool that would define problem areas and guide future studies.

2.2 KEY INTERFACE ACTIVITIES/GUIDELINES

The key interface activities/guidelines are presented for the three major subsystem categories: Electric power and distribution, thermal control and EMC. For purposes of reducing the immense quantities of intertwining data that the experimental subelements would provide, the initial objective of this study was to concentrate on two subelements (biological and furnace) thereby refining the study approaches for the remaining aspects of the program.

2.2.1 Electric Power and Distribution Subsystem

Earlier studies indicated that virtually all SPA equipment will require special conditioning of the input power (high voltage, low voltage, regulation, etc.). An examination of the input power conditioning available from the Spacelab indicated a possible mismatch in special equipment requirements for a majority of cases including commercial equipment. Maximum flexibility in integrating subelements into the Spacelab is achieved if the conditioners are not centralized, but are part of the equipment. Central activities were directed toward defining equipment requirements (more than just power level) and toward establishing minimum equipment complements for flight hardware. At the commencement of the study it appeared that power conditioners would be provided for each of the minimum equipment complements. One potential alternative that was considered was that modification of existing equipment designs could be implemented to standardize input power characteristics in order to operate either directly from the Spacelab power buses or from modular standardized power conditioners (partially centralized). A simple electrical interface between subelements and the Spacelab (or other power source/vehicle) appears to be mandatory. When considering different types of power that may be available from the Spacelab (AC, DC, different voltages/frequencies) each subelement must be examined to establish which source yields the best compromise between power conditioner reliability, efficiency, weight, etc. Wherever appropriate, the selected power type must also be available from power sources other than Spacelab.

Another aspect that must be considered for the electric power subsystem interface analysis is the protection of the power source against overloads in the subelement equipment or wiring. Overloads may result from large peak power requirements and are an interesting problem especially in the situation when all power comes from Spacelab on a single bus. The entire area of fault protection has been scrutinized during this study.

Power conditioning and distribution equipment efficiencies have a direct impact on thermal control requirements. Conversely, thermal control requirements may have a direct impact on power conditioner sizing (if conditioning is required for pumps, fans, etc.). This iterative analysis of the electric power/thermal control interface was a key study activity.

Consideration has been given to peak power requirements that may impose excessive voltage drops in power buses or excessive cable weight to achieve acceptable voltage drop at the using equipment. In addition, the energy content of the peaks may be better supplied from, or supplemented by, batteries in the subelement itself. This would minimize the impact of the power requirements on the sizing of Spacelab power equipment. The intent of this consideration is to devise subelements that can fit into a given vehicle design without necessitating major modifications. It became apparent that consideration must be given to batteries and fuel cells in the subelements. The type of battery or fuel cell and associated controls were reviewed and selected. The power sources' large, variable heat dissipation, as well as their performance sensitivity to temperature, create a major thermal interface analysis activity.

2.2.2 Thermal Control Subsystem

The Spacelab thermal interfaces under evaluation pertain to the waste heat rejection requirements of the subelements. The heat rejection capability that is supplied by the configured Spacelab dictates the direction and emphasis of the study. Heat dissipation by moderate temperature range equipment may be handled by the excess capability of the Spacelab. Waste heat from high temperature source (furnaces typically) can most efficiently be handled using a high temperature auxiliary radiator. Identification and separation of the subelement waste heat into candidates for Spacelab removal or high temperature radiator removal was the initial task of the study. In conjunction with waste heat rejection, equipment temperature control was included as an important aspect of the thermal design. Achieving temperature distributions in the region of high temperature furnaces or cooling units

which are compatible with component touch or condensation temperature limits became a major consideration of the thermal control system design. The equipment investigated for the two prototype subelements was categorized according to the need for additional thermal control for temperature compatibility.

The interfaces of the thermal control system with the subelement equipment were examined to ascertain potentially desirable modifications to equipment that would reduce the thermal control problems; for example, the addition of a small blower within equipment that is normally air cooled by natural convection could negate the need for surface temperature control.

The physical interfaces with Spacelab and the Shuttle cargo bay, created by the need for an auxiliary radiator, include the location of fluid lines and requisite penetrations of the pressure shell to accommodate radiator requirements. Location of the radiator itself must, therefore, be compatible with other aspects of the selected orbiting configuration.

The physical interfaces with experiment equipment may necessitate the nee. for auxiliary ducting for air cooling the moderate temperature range equipment and may create additional interfaces with the Spacelab air distribution system. The payload ducting, if fed from the Spacelab system, must be compatible with the pressure distributions within the existing ducting. Otherwise additional fans (compressors) would be required to provide the necessary cooling. A trade-off between the prime mover power and the heat rejection was conducted to assess the feasibility of air cooling.

2.2.3 EMC Subsystem

The EMC tasks and activities were directed toward attaining the following system assurances: (1) that no degradation or malfunction of the SPA system is caused by unintentional electromagnetic interactions between elements of SPA or with the electromagnetic environment in which it is embedded, and (2) that the SPA system does not degrade or cause malfunctions in other systems operating in that environment. These tasks were approached by reviewing both electromagnetic

interference (EMI) emissions and EMI susceptibility of elements of SPA to ensure that a margin exists between the EMI environment and the susceptibility of all elements which must operate in that environment.

A significant interface exists in the area of relating other users' systems with which SPA must be electromagnetically compatible. In the EMC activity, other users must be considered both as culprits and as victims in assessing EMC. Within the context of exploiting every mission opportunity, SPA should be capable of operating in close proximity to such experiments as high energy science involving wideband receivers. Both the range of levels and the range of frequencies to be considered in in the EMC studies were broader than is normal in space systems EMC analysis.

An additional factor that contributes to the EMC subsystem interface with the other subsystems is that most commercial equipment of the kinds envisioned for SPA have not had to consider EMC in the broad sense that is necessary with space systems. This problem affects not only SPA internal EMC, but also EMC within the Spacelab/Shuttle environment.

The magnitudes of the currents, voltages and powers processed within some components envisioned for SPA indicate that the EMI emissions from SPA will be abnormally high for space systems. The inclusion of radio frequency (RF) sources working in housing with necessary optical aperatures, which necessarily reduces shielding effectivity, can be expected to contribute to these high levels of EMI in the SPA environment. In practice, this characteristic implies that SPA is more likely to be an EMC culprit than an EMC victim.

2.3 ENGINEERING DISCIPLINES' SUBSYSTEM REQUIREMENTS

2.3.1 Electric Power and Distribution Subsystem

To establish power conditioning and distribution configurations, it was necessary to determine electrical characteristics of the available types of power sources and the experiment loads at the outset of the study. Where the characterisitics selected for the study were relatively broad, the study addressed the sensitivity of subelement performance and the power required to accommodate experiments during these "delta" variations.

Configuration concepts of the power conditioning and distribution subsystem were strongly influenced by such prudent factors as integration, testing and physical constraints in addition to those of electrical power inputs, outputs, control and protection requirements.

2.3.2 Thermal Control Subsystem

The thermal control subsystem provides the required thermal protection to maintain all subsystems and experimental equipment within thermal limits for all mission phases.

Waste heat dissipation timelines were constructed for the equipment needed in certain exemplary experiments selected for the subelements to be studied. The timelines were necessary to establish magnitude and duration of peak loads. The method of handling peak loads, e.g., use of primary structure as a heat sink versus provision of additional heat sink material was somewhat dependent upon their characteristics. Allowable component temperature information was required to assess the temperature control mechanisms available. The need for liquid loop thermal control versus air cooling can depend on the heat dissipation and allowable temperature of the equipment to be thermally controlled. Typical equipment packaging information was required to select a thermal control system. The location of heat dissipating equipment relative to the exterior envelope, structural members and other heat dissipating equipment, impacts the choice of a thermal control system. Information regarding the physical shape of the heat dissipating components was necessary to identify the level of forced air flow necessary to compensate for the cooling that would normally be provided by natural convection.

In the case of the Spacelab, the air flow characteristics of the Spacelab were required for use in the thermal control system sizing and trade-off analyses. Local cabin velocities, duct pressure distributions and equipment container flows were required to properly assess the air cooling concepts. Thermal characteristics of the Spacelab were required to conduct trade-off studies. Interior temperature distributions were required to establish the thermal radiation environment for equipment heat dissipation analyses. Physical information on the Shuttle bay/Spacelab envelope was necessary to locate auxiliary radiator(s) with

attendant interfaces. The available area for locating a radiator dictates the thermal control scheme alternative that may be chosen.

2.3.3 EMC Subsystem

A majority of the data required for a detailed EMC study is not readily avaialable; therefore, much of the analyses accomplished was based on assumed levels, frequencies, configurations, etc.

Two general approaches to the EMC program presently in use are: (1) the military specification approach, and (2) the mission-specific analytical approach. The military specification approach utilizes a specification document providing a broad range of requirements on component emissions of, and susceptibility to, EMI. Historically, the point of control has been in the acceptance testing of the components. The intent of the military specification approach was to ensure that components qualified to the specified requirements could be integrated into a system with minimal EMC problems which is a viable approach if rigorously enforced for long lifetime systems. Unfortunately, such an approach has often resulted in over-designing from an EMC point of view, and severe cost and weight impacts have been incurred which were unnecessary.

The mission-specific analytical approach to EMC utilizes an EMC specification as a start. Analysis, using a computer EMC model of the system, would be performed during implementation of the system design and would be verified by testing during component and system assembly. Thus, the point of control is shifted into the design phase. Design trade-offs involving EMC constraints could be made rationally, with the computer model as an analytical tool. Rigorous enforcement of a military specification approach would dilute the advantage of the mission-specific approach with regard to design trade-offs, but the computer analysis could still shift the EMC control point into the design phase

The point of concern is that the SPA approach to EMC must reflect the Spacelab and Shuttle approaches which are as yet undefined.

3. ELECTRICAL POWER SUBSYSTEM

The major concerns of the electrical power subsystem have been to review and evaluate the electrical power demands of various SPA experiments as they relate to:

- Power availability
- Power capability
- Energy demand
- Evaluation of supplemental power sources

These studies will then provide the basis for concept evaluation and comparisons for supplemental power sources and power conditioning and distribution for Spacelab. Each of the above has been evaluated during the continuing SPA program study activities.

3.1 POWER REQUIREMENTS

There are a vast number of possible SPA experiments. For the purpose of narrowing the scope of this study, the equipment and load profiles for twelve representative experiments have been identified. Two experiments were chosen from each of the six basic research and development (R&D) categories. The twelve representative experiments are listed in Table 1 by name, along with the R&D category and equipment subelement in which it would be performed. Throughout the body of this report, the twelve experiments will be identified by the numbers one through twelve. Two of these experiments, chosen as representative of the twelve, have been identified in greater detail to assist in the necessary evaluations of this study. They are: Experiment #1, Metallurgical-Furnace, Encapsulated Immiscible Combination; and Experiment #8, Biology Application-Biological, Continuous Flow Electrophoretic Separation of Proteins.

3.1.1 <u>Equipment Power Load Profiles</u>

During the previous phase of the SPA study, surveys were conducted to determine applicable experiment equipment in each of the subelement categories and to obtain operating character stics and related data for as much of the experiment equipment that was commercially available. No

Table 1. SPA Experiment Identification

No.	Exemplary SPA Experiment Class	R&D Category	Subelement
1.	Encapsulated Immiscible Combination	Metallurgical	Furnace
2.	Preparation of Pure Alloys - Containerless Melting	Metallurgical	Levitation
3.	Molten Zone Crystal Growth	Crystal Growth	Furnace
4.	Crystal Growth by Pulling from a Containerless Melt	Crystal Growth	Levitation
5.	Preparation of Multiphase, Silicate-Based Glass	Glass Technology	Furnace
6.	Containerless Preparation of La_2O_3-Based Glass	Glass Technology	Levitation
7.	Stationary Column Electrophoretic Separation of Proteins	Biology Applications	Biological
8.	Continuous Flow Electrophoretic Separation of Proteins	Biology Applications	Biological
9.	Containerless Position Control of Liquids by Electromagnetics	Physical Processes in Fluids	Levitation
10.	Thermal Gradient Convection in Liquids	Physical Processes in Fluids	General
11.	Chain Reactions Affected by Convection	Chemical Processes in Fluids	Levitation
12.	Radical Lifetimes	Chemical Processes in Fluids	General

attempt was made to select particular equipment but the approach taken was to determine the characteristics of typical equipment that could be used.

From the results of these surveys, typical equipment was listed for the twelve representative experiments and noted in Section 3.1.2. Further detail was obtained for two of the twelve experiments that were selected as representative of the twelve. A summary of the equipment required and their electrical power characteristics are contained in Table 2 for the Metallurgical-Furnace (Encapsulated Immiscible Combination) experiment and in Table 3 for the Biology Applications-Biological (Continuous Flow Electrophoretic Separation) experiment. Each of the experiment equipment items are identified by name and by equipment number. The operating power is the power required to maintain the operation of the equipment item. The energy requirement is for one experiment cycle. All of the equipment items require a 115/230 VAC, 60 Hz input that could operate at ranges to 400 Hz. Those equipment items that are shown to require a different input have been provided with a power conditioner as part of the equipment. Although the power conditioners are part of the equipment items that they supply, the conditioners are listed separately. The power requirements listed are inputs to the power conditioners which are 115/230 VAC, 60 Hz inputs.

All equipment items for the two experiments are listed in Tables 2 and 3, but all do not require power. In Table 2, the Hot Wall Furnace (F2E) contains a Resistance Heater (F18E) that is supplied power from a Low Volt/High Amp Power Conditioner (F15E). Power is required only to the power conditioner. Power is supplied to the High Vacuum Pump (F2SE) from the Vacuum Pump Power Conditioner (F30E). The Molecular Sieve (F28E) does not require electrical power.

The Continuous Flow Electrophoretic Column (B11E) for the Biology Applications Experiment (Table 3.) is supplied power from the High Voltage (5 kV) Power Conditioner (B21E). No power is required for the supply tanks B14E and B20E or for the waste liquid tank B26E.

The power requirements for each of the equipment items assigned to the Core Subelement that is used to support the SPA experiments, is

Table 2. Experiment Equipment Load Requirements

1. Metallurgical - Furnace

(Encapsulated Immiscible Combination)

EQUIPMENT NAME	EQUIPMENT NO.	POWER, KW		PEAK DURATION	KWH PER CYCLE	TYPE AND QUALITY		MISCELLANEOUS
		OPERATING	PEAK			VOLTAGE	FREQUENCY, Hz	
HOT WALL FURNACE, 1800°C MECHANICAL MIXING	F2E	0.000	-	-	-	-	-	SEE F15E*
AND DISPERSAL UNIT	F21E	0.025	0.125	SPIKE	0.004	115 VAC	60	
RESIDUAL GAS ANALYZER	[illegible]2E	0.250	0.500	SPIKE	0.456	115 VAC	60	
LOW VOLT/HIGH AMP POWER CONDITIONER	F15E	5.000	14.000	30 MIN	7.700	208/230 VAC	50/60	POWER TO FIRE*
PIEZOELECTRIC DRIVE	F23E	0.005	0.055	SPIKE	0.003	115 VAC	60	
RESISTANCE HEATER	F18E	-	-	-	-	4 - 6 V	DC	PART OF F2E*
VACUUM/PRESSURE REGULATOR	F24E	0.050	0.150	SPIKE	0.100	115 VAC	60	
HIGH VACUUM PUMP	F25E	-	-	-	-	4.75 KV	DC	POWER FROM F30E**
VACUUM PRESSURE MEASUREMENT UNIT	F26E	0.050	0.150	SPIKE	0.100	115 VAC	60	
MOLECULAR SIEVE	F28E	0.000	-	-	-	-	-	NO POWER REQUIRED
VACUUM PUMP POWER CONDITIONER	F30E	0.100	1.100	12 MIN	0.484	115/220 VAC	60	POWER TO F25E**

*RESISTANCE HEATER (F18E): HEATING ELEMENT FOR HOT WALL FURNACE, 1800°C (F2E); SPECIAL REQUIREMENTS FOR RESISTANCE HEATER (F18E) PROVIDED BY LOW VOLT/HIGH AMP POWER CONDITIONER (F15E).

**SPECIAL REQUIREMENTS OF HIGH VACUUM PUMP (F25E) PROVIDED BY VACUUM PUMP POWER CONDITIONER (F30E).

Table 3. Experiment Equipment Load Reqirements

8. Biology Applications-Continuous Flow

(Electrophoretic Separation)

EQUIPMENT NAME	EQUIPMENT NO.	POWER, KW		PEAK DURATION	KWH PER CYCLE	TYPE AND QUALITY		MISCELLANEOUS
		OPERATING	PEAK			VOLTAGE	FREQUENCY, Hz	
FLUID COOLING/REFRIGERATION UNIT	B1E	0.750	2.350	54 MIN	2.490	115 VAC	60	
UV-VIS SPECTROMETER	B5E	0.200	0.400	SPIKE	0.140	115 VAC	60	
PUMPS (METERING)	B10E	0.100	-	-	0.080	115 VAC	60	TWO PUMPS
		0.100	-	-	0.070	115 VAC	60	
CONTINUOUS FLOW ELECTRO-PHORETIC COLUMN	B11E	-	-	-	-	25 - 2500 V	DC	POWER FROM B21E*
GAS ELIMINATION SYSTEM	B13E	0.050	0.100	SPIKE	0.040	115 VAC	60	
REGULAR BUFFER SUPPLY AND ELECTROLYTE SUPPLY TANK	B14E	0.000	-	-	-	-	-	NO POWER REQUIRED
PH MONITOR	B15E	0.020	0.040	SPIKE	0.016	107-127 VAC 214-254 VAC	50/60	0.2 AMP 0.1 AMP
FRACTION COLLECTION SYSTEM	B16E	0.050	0.100	SPIKE	0.010	115 VAC	60	
FLOW METERS	B17E	0.010	0.020	SPIKE	0.008	115 VAC	60	
DISSOLVED OXYGEN ANALYZER	B19E	0.015	0.030	SPIKE	0.012	115 VAC	50/60	
SPECIMEN SUPPLY TANKS	B20E	0.000	-	-	-	-	-	NO POWER REQUIRED
HIGH VOLTAGE POWER CONDITIONER (SKV)	B21E	0.020	0.220	SPIKE	0.014	115 VAC	60	SUPPLIES POWER* TO B11E, N - 90% 25 - 2500 VOLT ±0.01
REFRIGERATOR	B23E	0.050	0.300	40 MIN	0.290	115 VAC	60	
WASTE LIQUID TANK	B26E	0.000	-	-	-	-	-	NO POWER REQUIRED

*SPECIAL REQUIREMENTS OF CONTINUOUS FLOW ELECTROPHORETIC COLUMN (B11E) PROVIDED BY HIGH VOLTAGE POWER CONDITIONER, 5 KV (B21E).

NOTE: Peak power of B1E should be 1.50 kW not 2.350. Revised June 1974.

listed in Table 4. Energy requirements are not included because the duration of operation of the Core Subelement equipment is dependent upon the experiment that is being supported. That is, the Core Subelement operates for about 3.5 hours for the Metallurgical-Furnace (Encapsulated Immiscible Combination) experiment and about 2.8 hours for the Biology Applications-Biological (Continuous Flow Electrophoretic Combination) experiment. Each of these durations are for one experiment cycle only. All equipment items are satisfied by a 115/220 VAC, 60 to 400 Hz input. The Fluid Supply System (C10E) does not require electrical power.

An electrical power load profile for each of the equipment items of the Metallurgical-Furnace (Encapsulated Immiscible Combination) experiment are presented in Figures 1(a) through 1(g). Each of the equipment items are phased from the beginning of an experiment cycle with zero elapsed time assumed to be the turn-on of the Core Subelement support equipment. These profiles are for all power required at the user equipment. A total equipment user load profile is obtained by adding the power required for each equipment item at each time to obtain the profile presented in Figure 1(h).

The equipment electrical power load profiles at the user equipment are presented in Figures 2(a) through 2(k), for Biology Applications-Biological (Continuous Flow Electrophoretic Column) experiment equipment items. A total equipment user load profile for the experiment is presented in Figure 2(1).

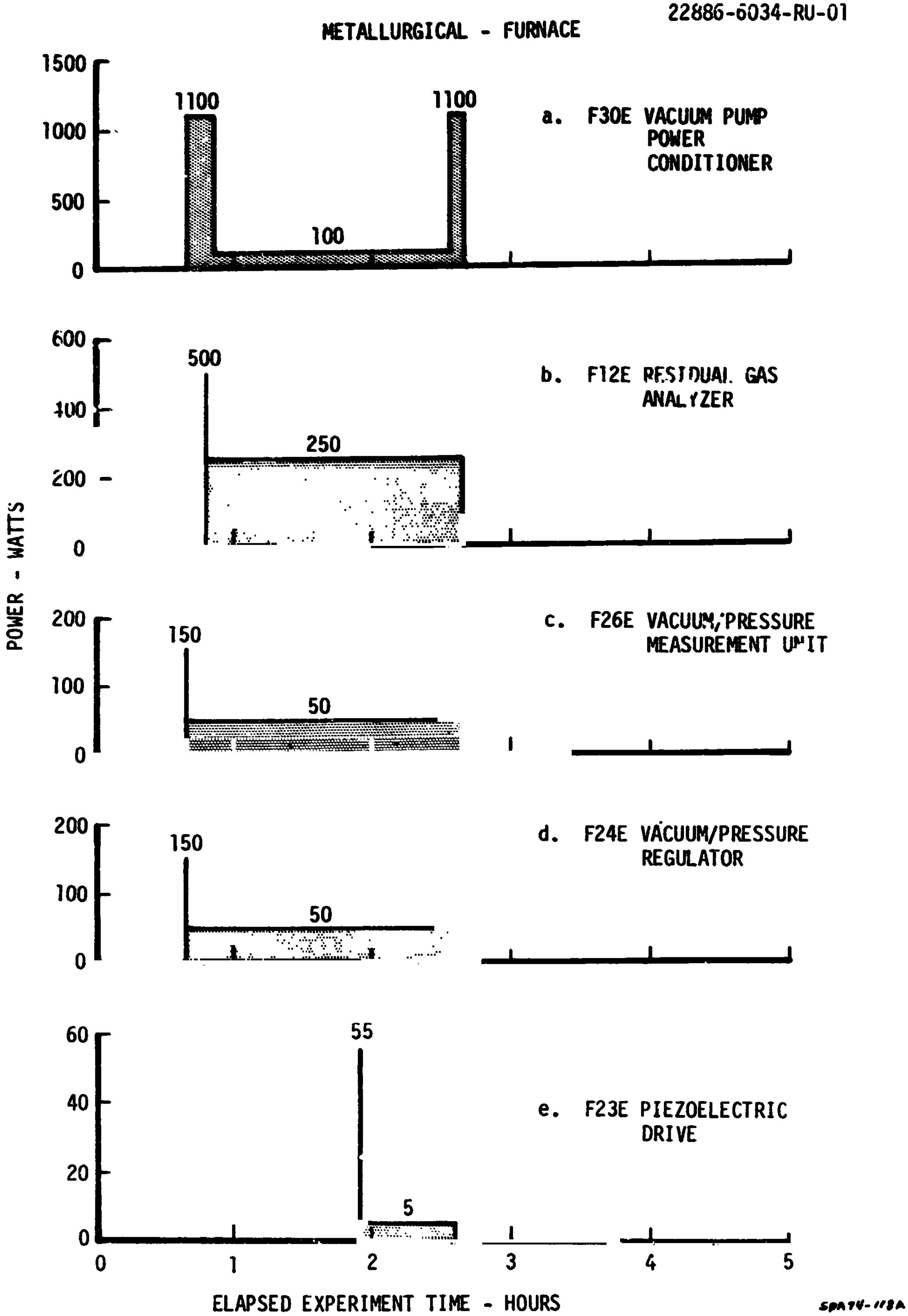
The equipment power profile for the Core Subelement used to support all of the SPA experiments is presented in Figure 3. This profile should be added to the experiment equipment profiles, Figure 1(h), and 2(1), to obtain the total experiment equipment profiles. The individual equipment profiles have not been defined separately because of the differences in requirements for each experiment, (principally in duration of operation). The average user power for the Core Subelement is about 1.8 kW with a peak power of about 2.1 kW for a maximum of 50 minutes. The durations to support the two selected experiments are indicated on the profile.

Table 4. Experiment Equipment Load Requirements

Core Subelement

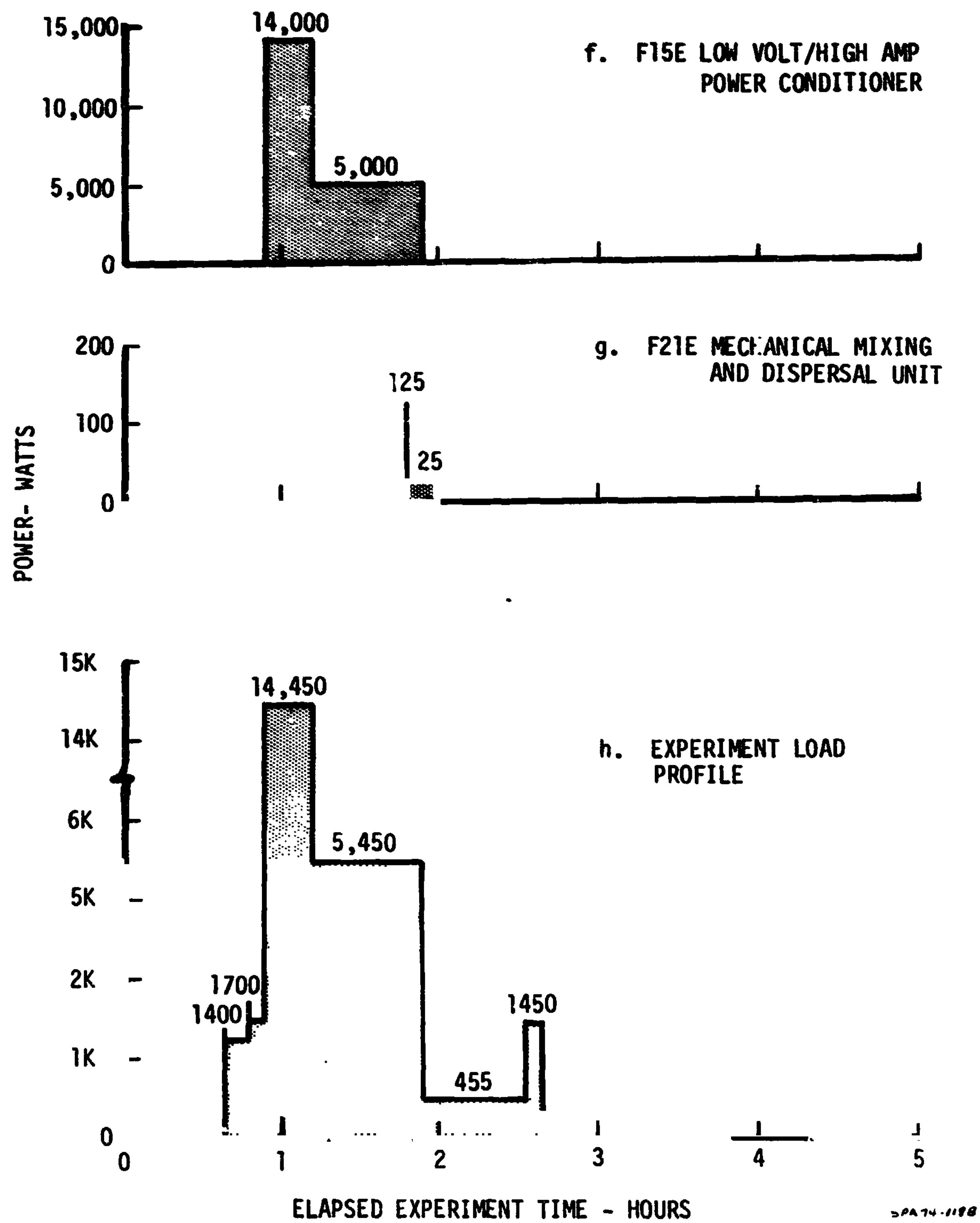
EQUIPMENT NAME	EQUIPMENT NO.	POWER, KW		PEAK DURATION	KWH PER CYCLE	TYPE AND QUALITY		MISCELLANEOUS
		OPERATING	PEAK			VOLTAGE	FREQUENCY, Hz	
DIGITAL CLOCK	C1E	0.010	-	-	DIFFERENT FOR EACH EXPERIMENT*	117 VAC	50/60/400	
SCANNER PROGRAMMER	C2E	0.060	-	-		115 VAC	50/60	0.5 AMP
SIGNAL CONDITIONER	C3E	0.035	0.290	50 MIN (MAX)		115 VAC	60	WARM UP
DIGITAL VOLTMETER	C4E	0.100	-	-		115 VAC	60	
SET POINT CONTROLLER	C5E	0.120	-	-		115 VAC	50-60	
PROCESSOR UNIT	C6E	0.200	-	-		115 VAC	60	
INPUT/OUTPUT STAGE	C7E	0.150	-	-		115 VAC	60	
OPERATOR CONTROL UNIT	C8E	0.150	-	-		115 VAC	60	
PRINTER (OUTPUT)	C9E	0.400	-	-		115 VAC	60	
FLUID SUPPLY SYSTEM	C10E	0.000	-	-		-	-	NO POWER REQUIRED
TELEPRINTER	C11E	0.062	-	-		115 VAC	60	
DIGITAL STORAGE	C12E	0.150	-	-		115 VAC	60	
ANALOG (SCR) CONTROLLER	C13E	0.100	-	-		115 VAC	60	
MUX A/D CONVERTER	C14E	0.100	-	-		115 VAC	50-60	1 ϕ
TAPE INPUT	C15E	0.170	-	-		111/230 VAC	48-416	±10% V
STORAGE PERIPHERALS	C16E	0.150	-	-		115 VAC	60	
AUTOMATIC PROCESSOR	C17E	0.775	0.775	2-5%		117/234 VAC	50-60	2-5% DUTY CYCLE
CCTV CAMERA		0.030	-	-		117/230 VAC	50/60	±10% V
CAMERA CONTROL UNIT		0.030	-	-		117/230 VAC	50/60	±10% V
FRAME STORAGE UNIT		0.125	-	-		105/250 VAC	50/60	
MONITOR		0.140	-	-		115 VAC	60	
SLOW SCAN SYNC AND SWEEP	C17E	0.020	-	-		115 VAC	60	
OSCILLOSCOPE	C18E	0.100	-	-		100/125 VAC	48-400	±10% V AND Hz

*KWH REQUIRED FOR CORE SUBELEMENT DIFFER FOR EACH EXPERIMENT - DEPENDENT UPON THE EXPERIMENT AND LENGTH OF TIME EXPERIMENT OPERATING.

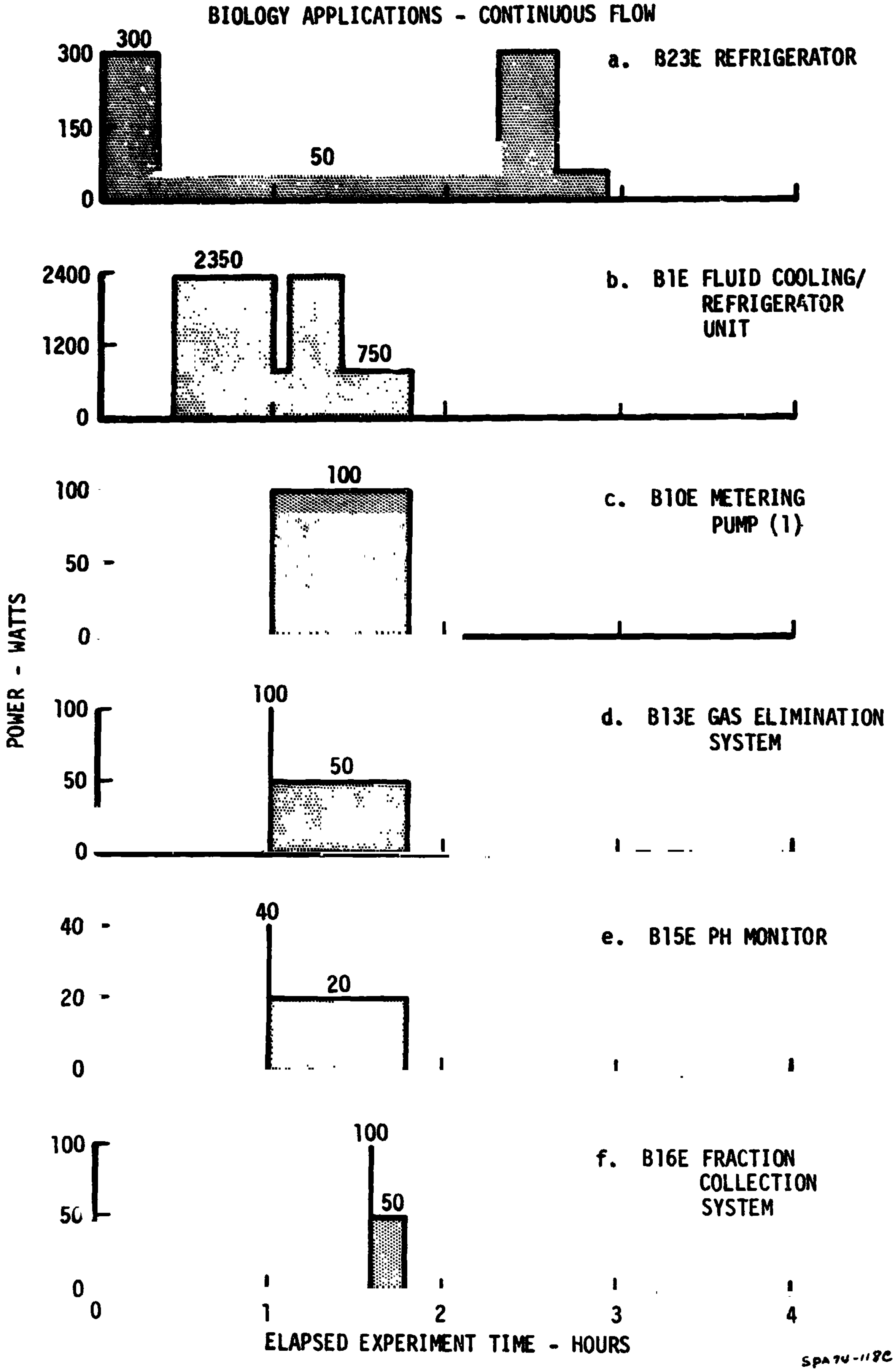


Figures 1a-e. Equipment Power Load Profiles.

METALLURGICAL - FURNACE



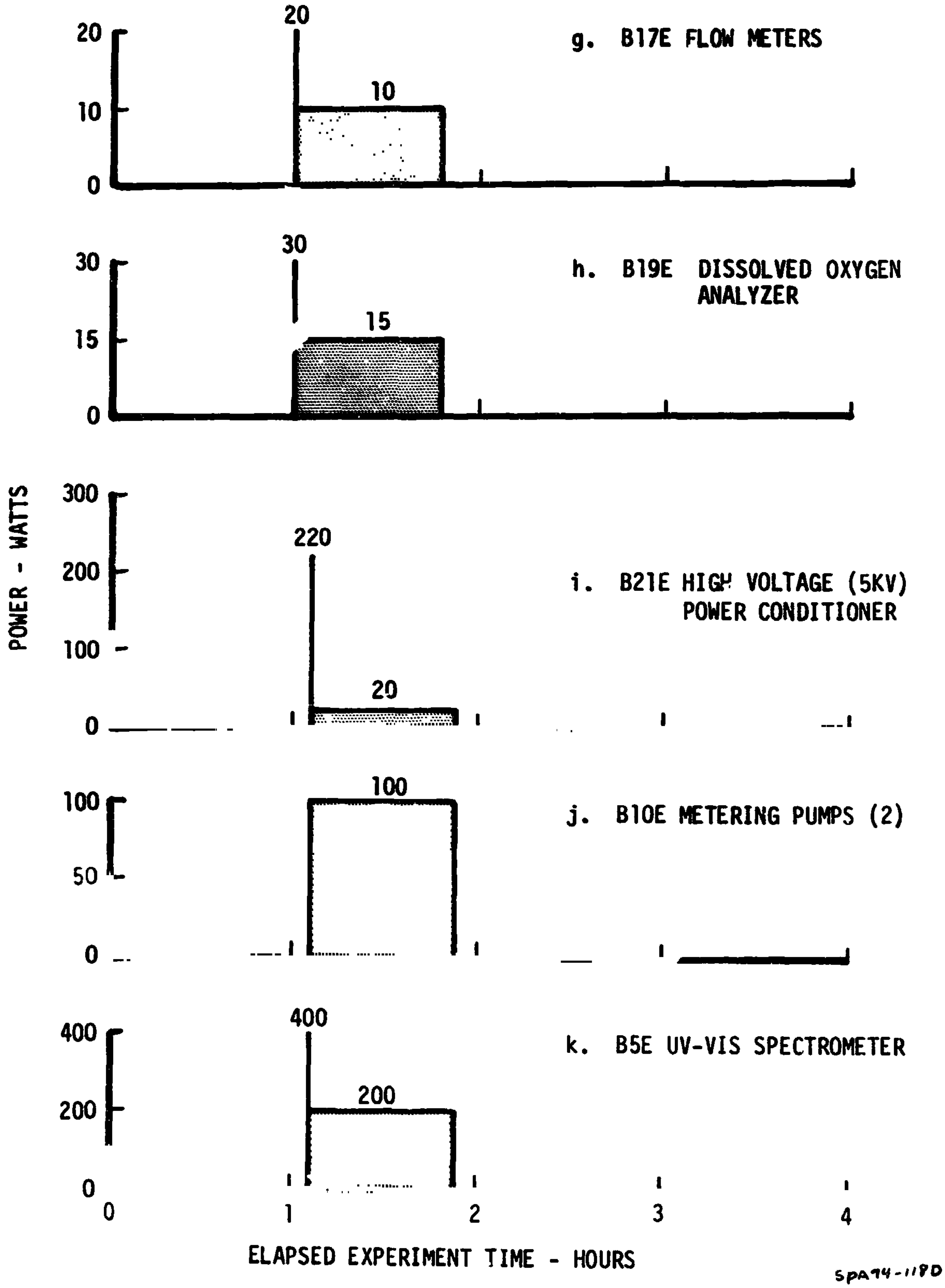
Figures 1f-h. Equipment Power Load Profiles.



Figures 2a-f. Equipment Power Load Profiles

NOTE: Peak Power of B1E should be 1.5 kW, not 2.35 kW as of June 1974.

BIOLOGY APPLICATIONS - CONTINUOUS FLOW



Figures 2g-k. Equipment Power Load Profiles

NOTE: Power profile should represent a peak power of the unit B1E as 1.5 kW not 2.35 kW which was revised in June 1974.

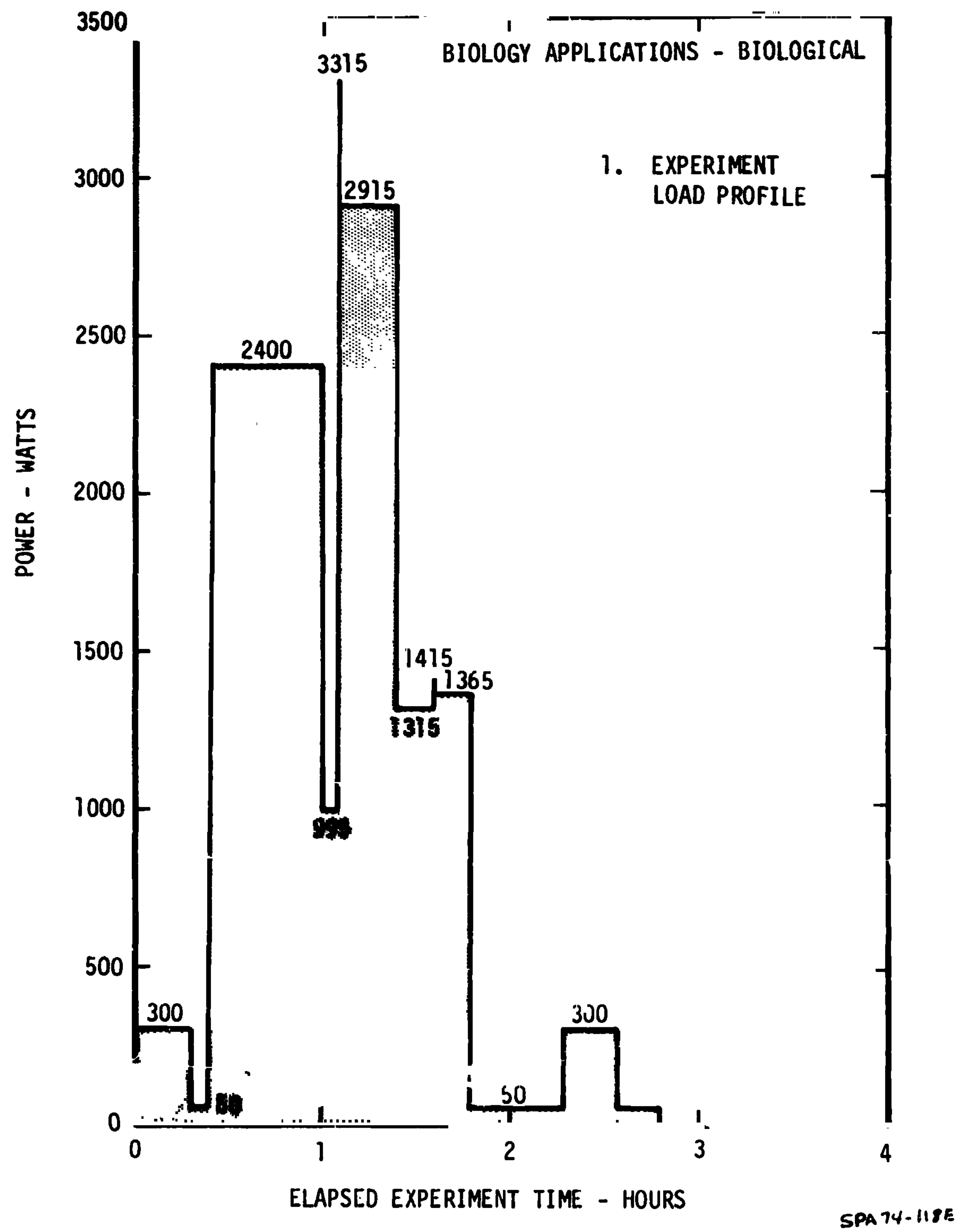


Figure 2(1). Equipment Power Load Profiles

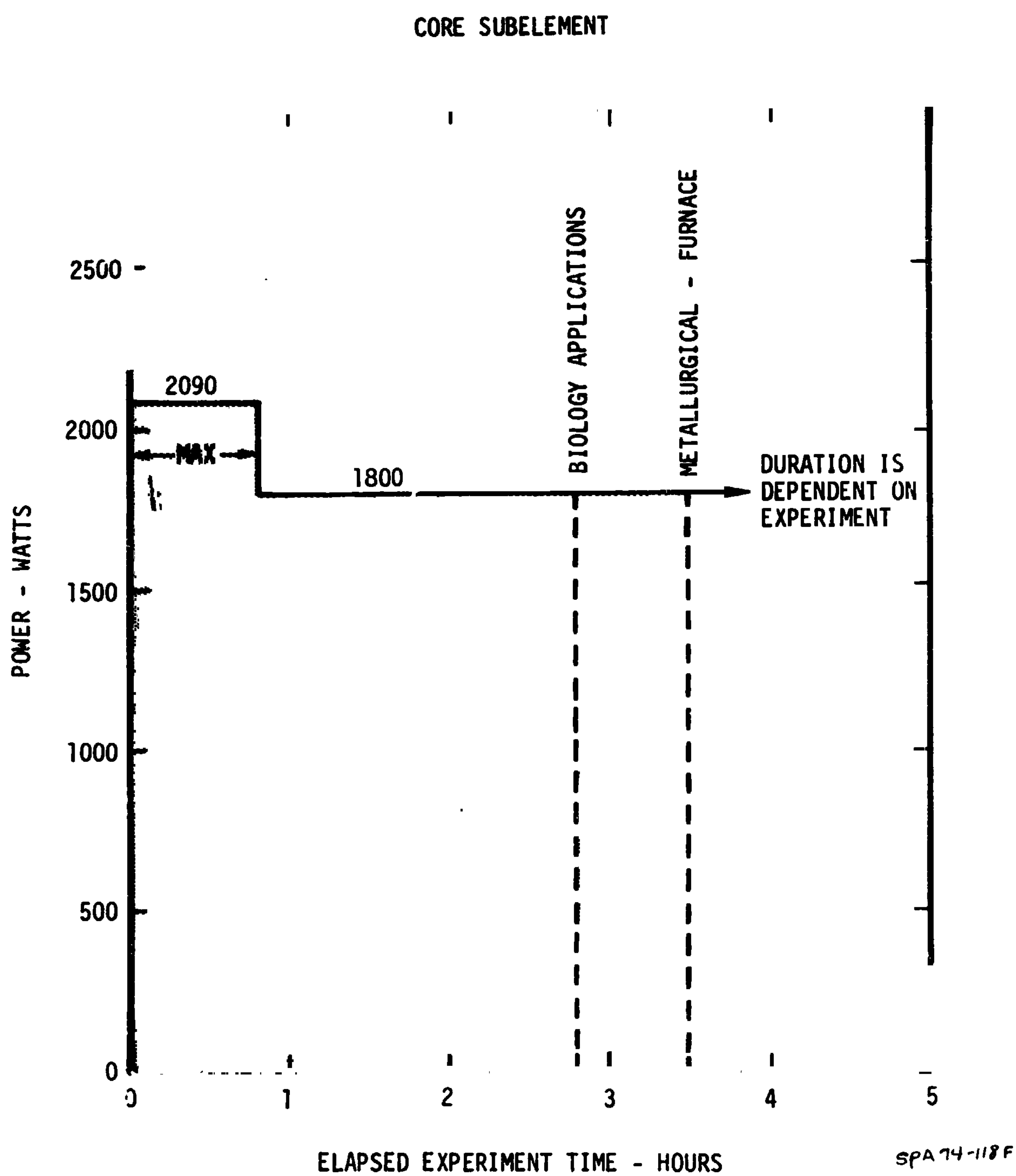


Figure 3. Equipment Power Load Profile Core Subelement.

A summary of the requirements for the two representative experiments is presented in Table 5. The average, sustaining and peak power requirements for the two experiments are also included. The average is expressed as the average power over the total elapsed experiment time from the time the core subelement supporting equipment is turned on until it is turned off. The time reference for this value is approximately one hour longer in duration than the experiment equipment operation. However, variations will occur and is dependent upon the experiment. The sustaining power is expressed as an average over the period of time that the experiment equipment is in operation. The time frame for this operation is usually a shorter time duration than for the average power. The peak requirements are keyed to individual profiles and are not additive. This factor is attributed to the condition that all of the peaks do not occur at the same time.

The experiment, core and thermal equipment requirements are electrical power requirements at the load user equipment. The subtotal of these values are reflected back to the power source assuming a 90% power factor, a 70% inverter efficiency, a 2% factor for line losses, and a 10% contingency. The load requirement summary is based upon all identified loads requiring AC power and reflecting these requirements back to a 28 volt DC electrical power source (see Section 3.2). The total values for each experiment for average, sustaining and peak power are electrical power requirements at the DC power source.

3.1.2 Experiment's Load Power Requirements

The twelve exemplary SPA experiments were analyzed in the same manner as the two that have been detailed in the previous section. Power profiles were prepared for each item of equipment and totals were obtained for the various power requirements at the experiment load.

The average, sustaining and peak power requirements at the user equipment for each of the twelve representative experiments and the Core Subelement are summarized in Figure 4. These values will be related to source power requirements in the following section. The figure shows the values for average, sustaining, peak power and the duration of each of the peaks. Where more than one peak occurs of similar magnitude both are presented.

Table 5. Electrical Load Requirements Summary
(115/200 Vac, 60-400 Hz, in kW)

ITEM	1. METALLURGICAL - FURNACE (ENCAPSULATED IMMISCIBLE COMBINATION)			8. BIOLOGY APPLICATIONS - CONTINUOUS FLOW		
	AVERAGE	SUSTAINING	PEAK	AVERAGE	SUSTAINING	PEAK
EXPERIMENT	2.03	4.42	14.45	1.22	1.13	3.32
CORE	1.80	1.80	2.09	1.60	1.80	2.09
THERMAL	0.47	0.47	0.47	0.47	0.47	0.47
SUBTOTAL	4.86	6.69	16.72	3.49	3.40	5.58
POWER FACTOR, 90%	0.54	0.75	1.86	0.39	0.38	0.63
CONVERTER EFFICIENCY, 70%	2.32	3.19	7.96	1.66	1.62	2.65
LINE LOSSES, 2%	0.16	0.22	0.54	0.11	0.11	0.19
CONTINGENCY, 10%	0.79	1.08	2.71	0.56	0.55	0.90
TOTAL	8.67	11.93	29.79	6.21	6.06	9.95

NOTE:
1. ALL PEAK DO NOT OCCUR AT SAME TIME; THEREFORE PEAK SUBTOTAL NOT A SUM.
2. AVERAGE: AVERAGE OVER TOTAL EXPERIMENT CYCLE OPERATION.
3. SUSTAINING: AVERAGE DURING EXPERIMENT EQUIPMENT OPERATION.

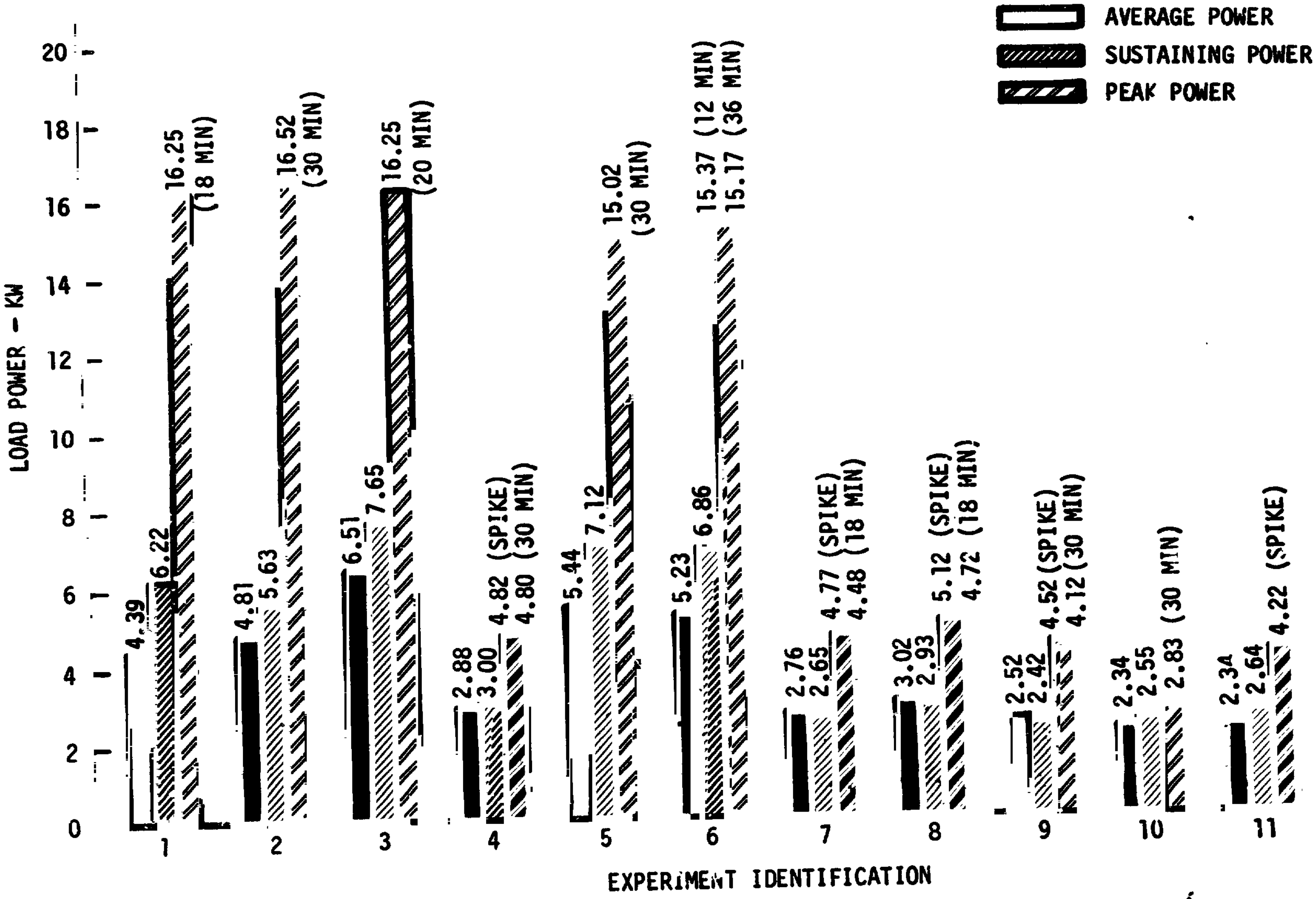


Figure 4. Experiment Load Power Requirements

Where two identical peaks occur with only several minutes of separation they are represented as one peak with a total duration equal to the sum of the duration of each peak.

The energies summarized in Figure 5 are for one experiment cycle and all energies required at the user equipment for both the experiment and Core Subelement equipment. The lower part of each bar represents the Core Subelement contribution to the total. These values must then be related to source energy requirements and subsequently multiplied by the number of experiment cycles in a mission to determine the total energy requirement.

3.1.3 Source Power Requirements

The electrical power requirements at the power source has several functions; it is used to size the power source and supplementary equipment and to assist in the EMI analysis and thermal control design. To obtain the electrical power requirements of the SPA experiments at the power source it is necessary to relate the experiment equipment load requirements through inverter inefficiencies and line losses to the electrical power source. This was accomplished for each of the twelve representative SPA experiments that were identified in this study. The results are shown as electrical power source profiles for each of the twelve experiments in Figures 6a-l.

The electrical power source profiles for each of the twelve experiments were obtained by combining the experiment equipment and Core Subelement equipment requirements presented in Section 3.1.2 with the thermal control equipment requirements. The values are then divided by 0.9 to account for an assumed power factor of 90%, divided by 0.7 to account for an inverter efficiency of 70%, divided by 0.98 to account for a 2% line loss and a 10% factor is added to the resultant subtotal to allow for a 10% contingency.

The average, sustaining and peak power requirements are indicated for each of the twelve experiments and the sustaining and peak values were summarized in Figures 7 and 8. These figures also compare the average and peak electrical power capabilities of one and two fuel cell systems.

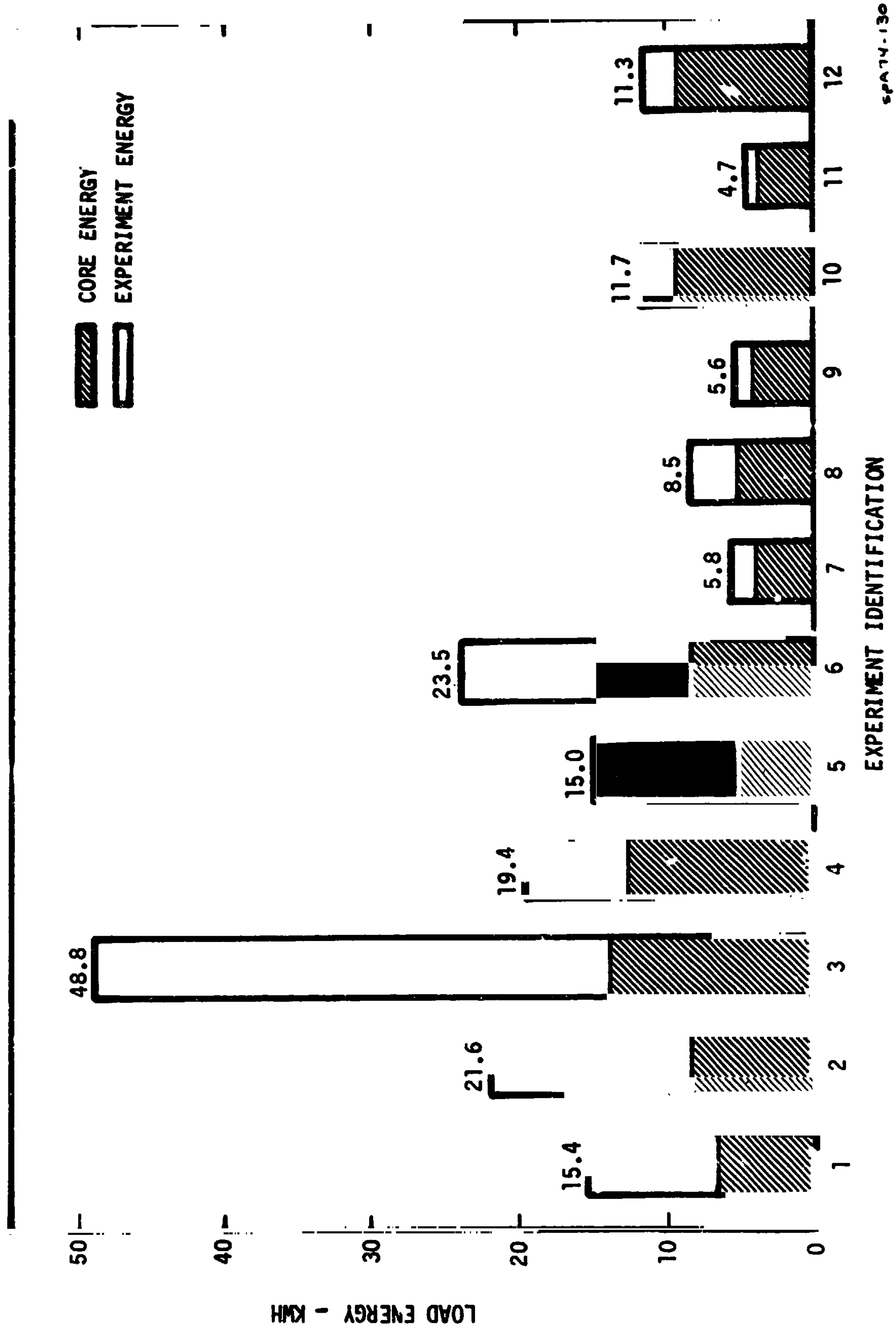
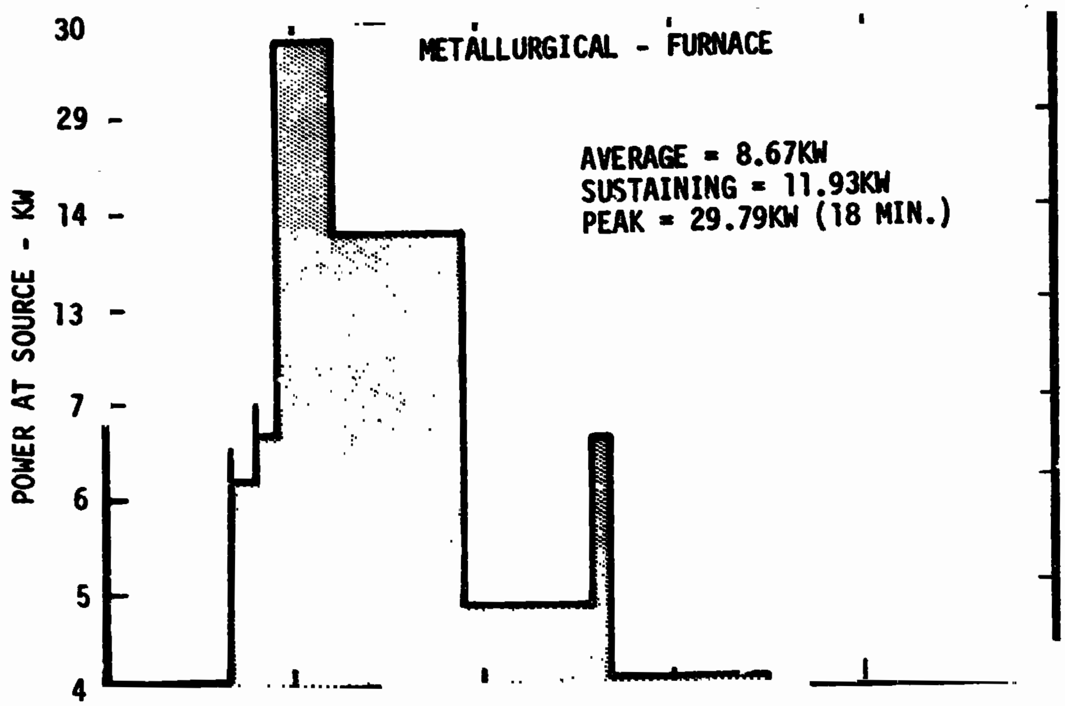
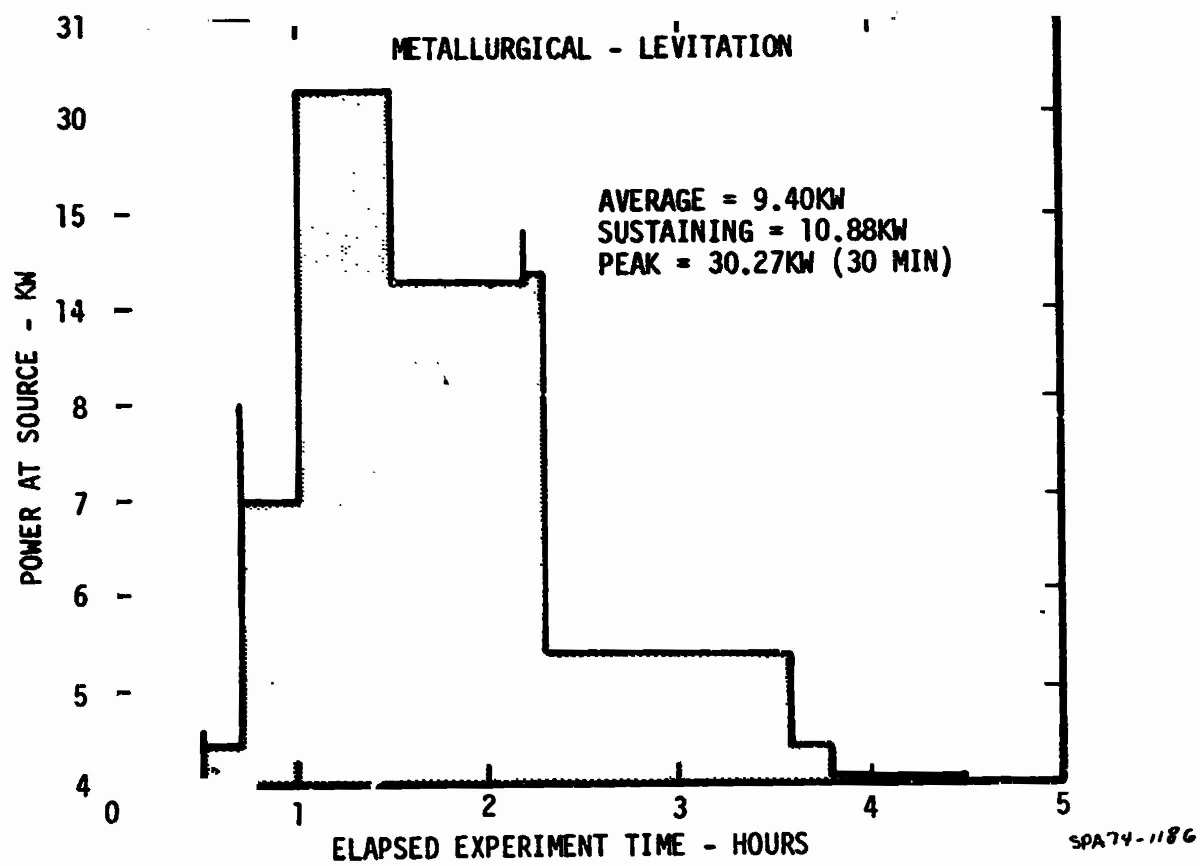


Figure 5. Experiment Energy Requirement Per Experiment Cycle

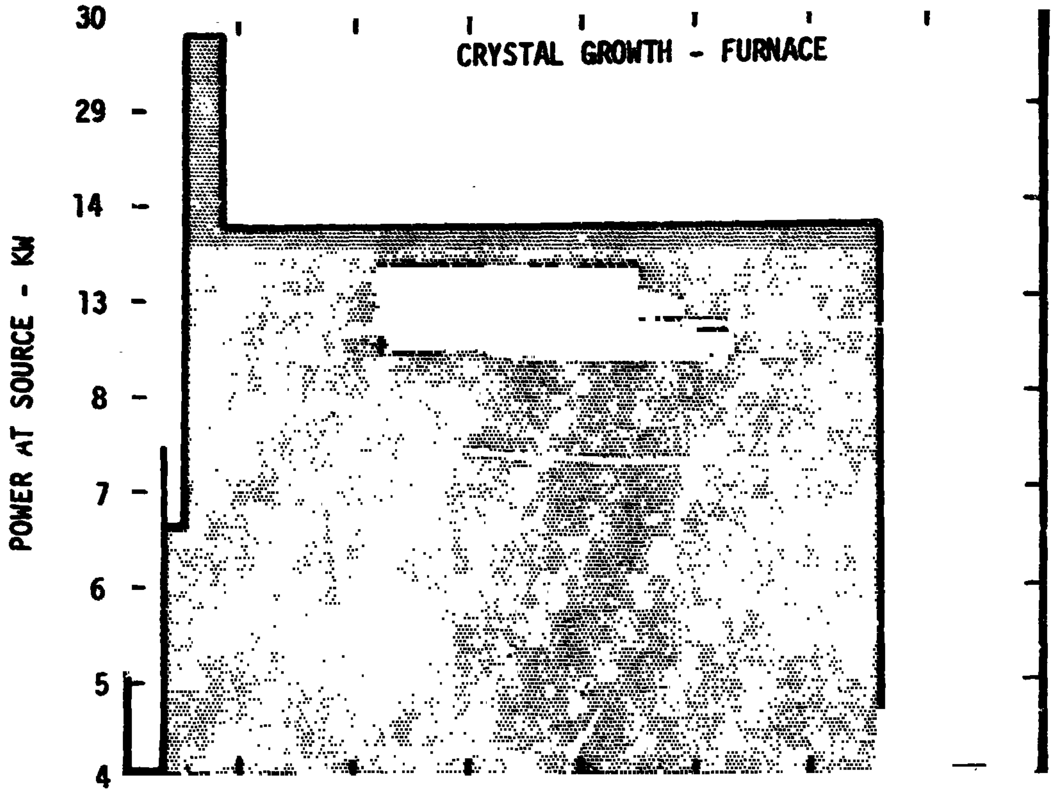


a. EXPERIMENT NO. 1

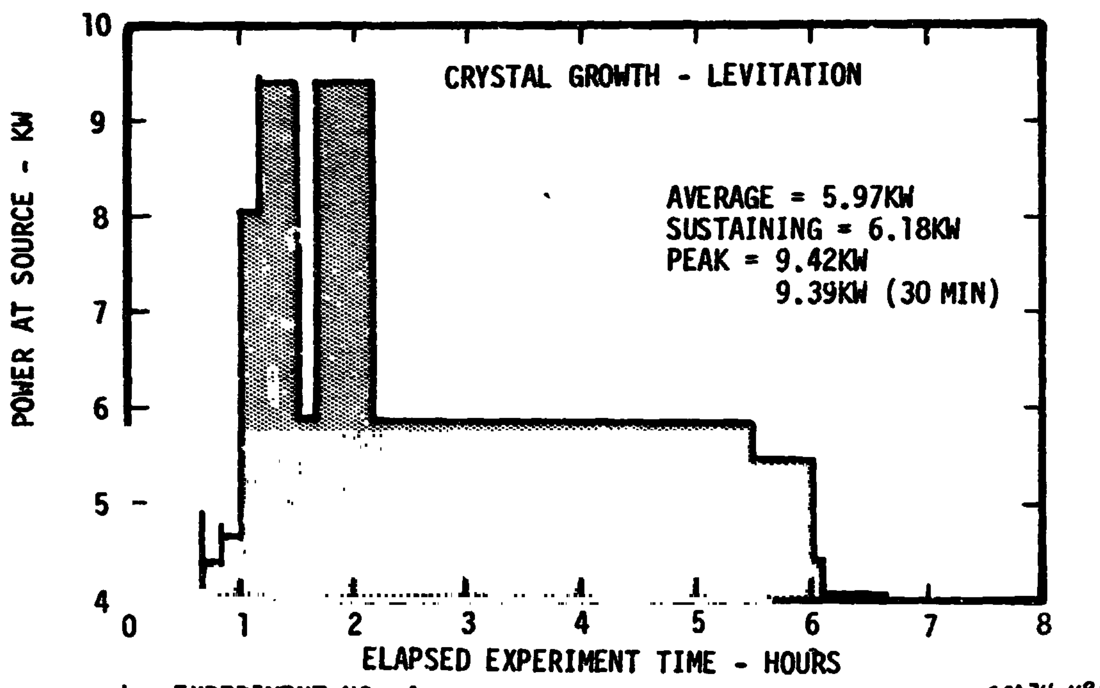


b. EXPERIMENT NO. 2

Figures 6a and b. SPA Experiment Power Source Load Profiles

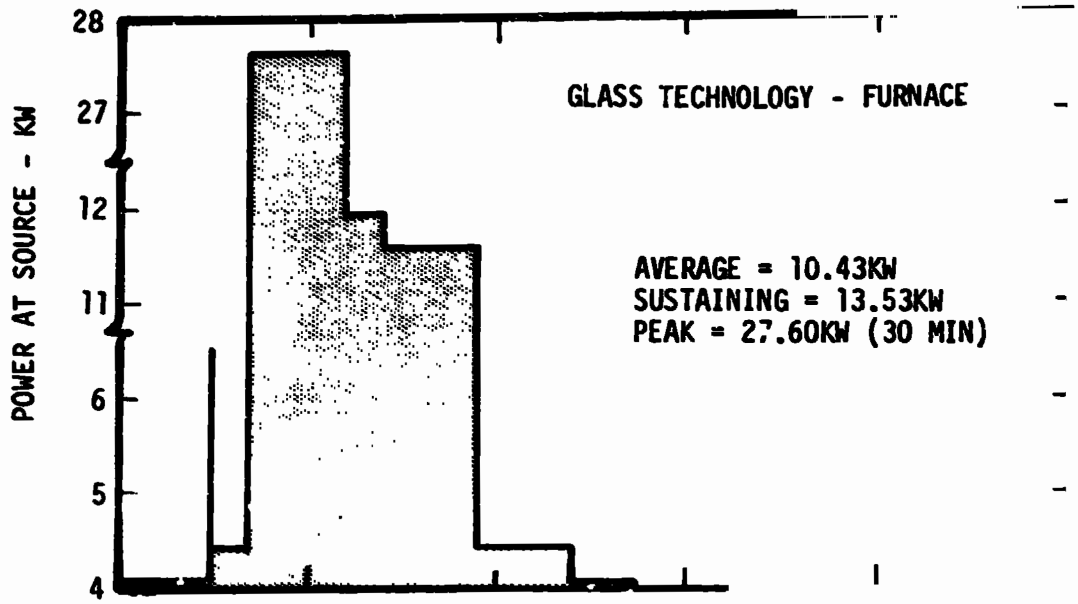


c. EXPERIMENT NC. 3

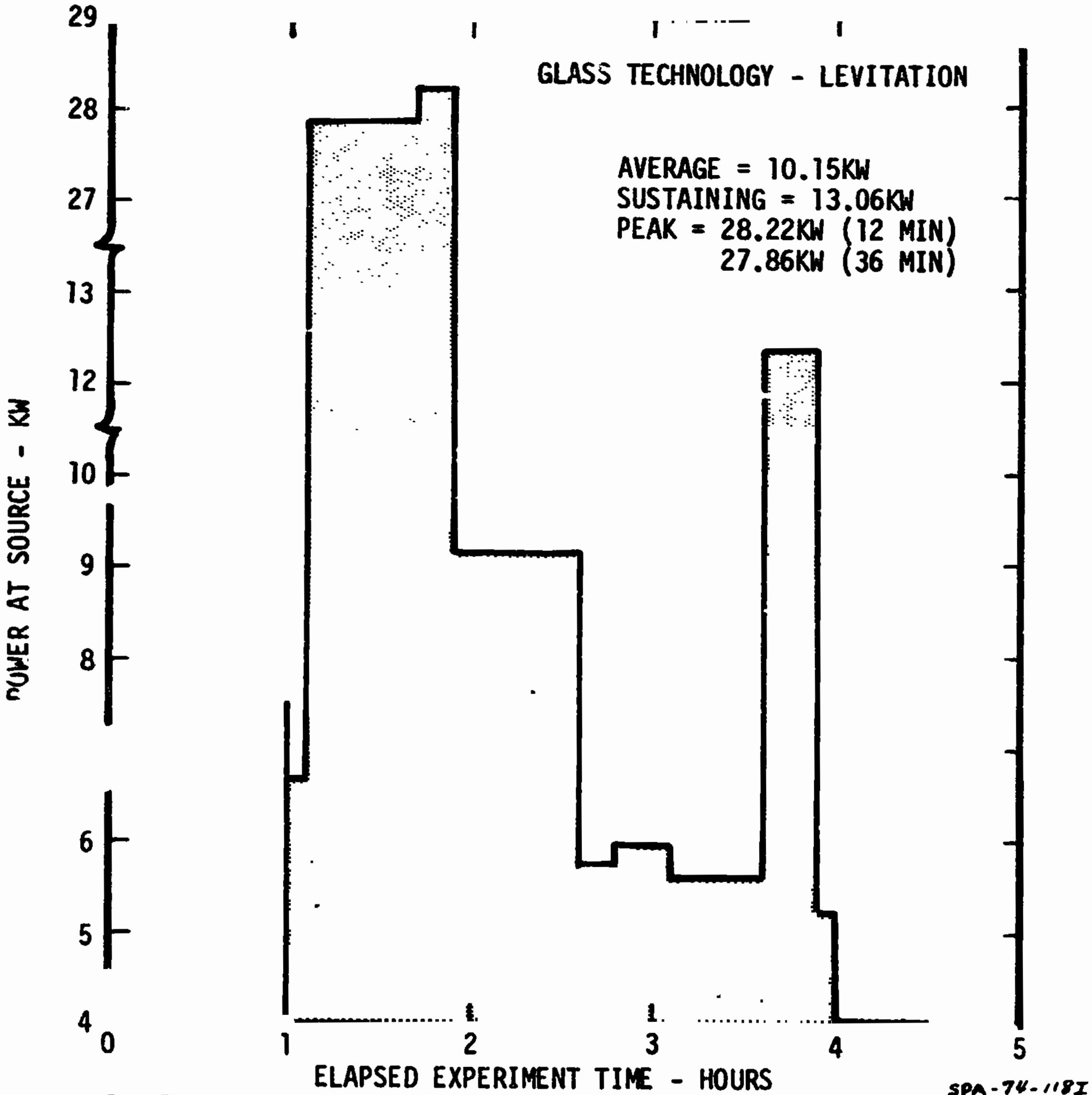


d. EXPERIMENT NO. 4

Figures 6c and d. SPA Experiment Power Source Load Profiles



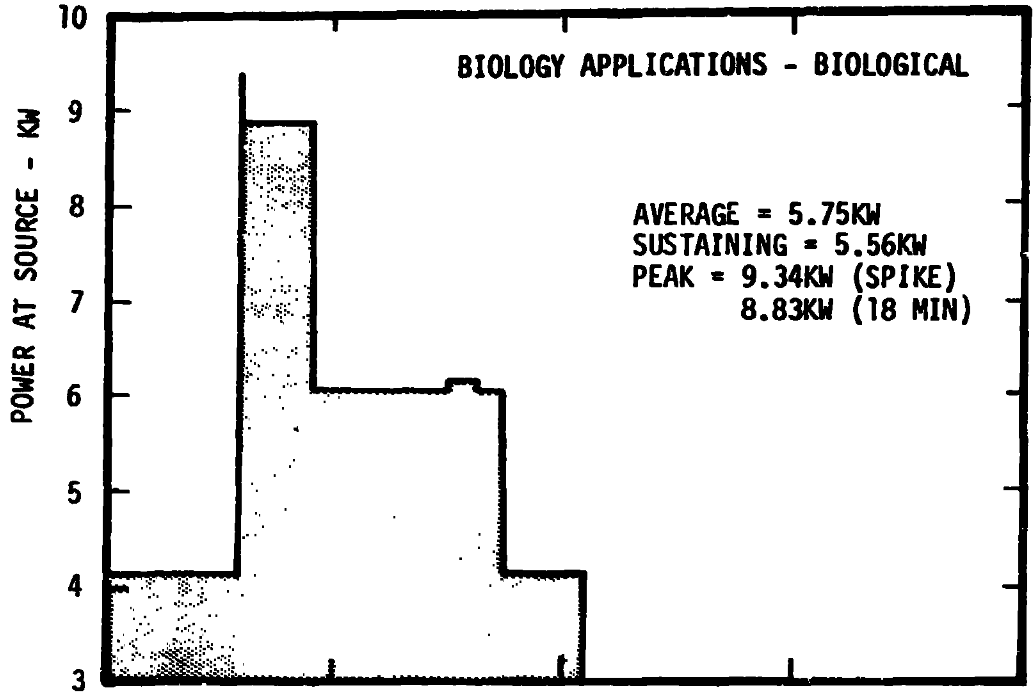
e. EXPERIMENT NO. 5



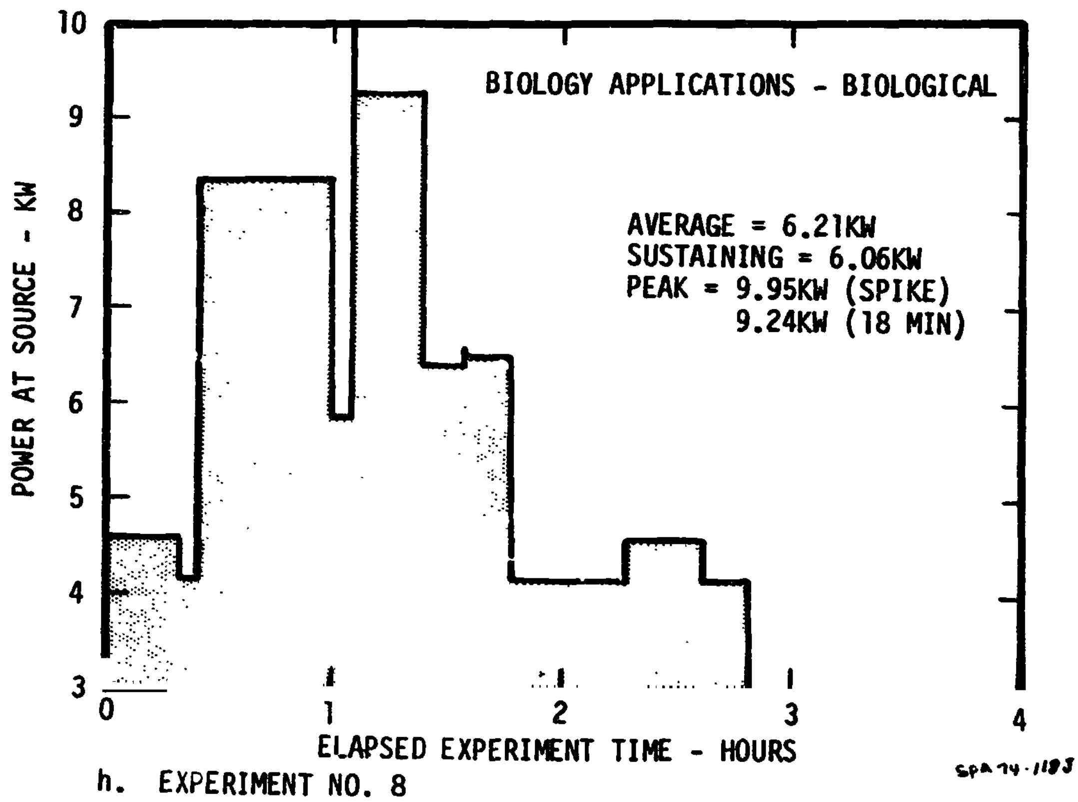
f. EXPERIMENT NO. 6

Figures 6e and f. SPA Experiment Power Source Load Profiles

NOTE: As of June 1974 the peak power of the unit B1E was revised to be 1.5 kW, which will change the appearance of the power profiles somewhat.

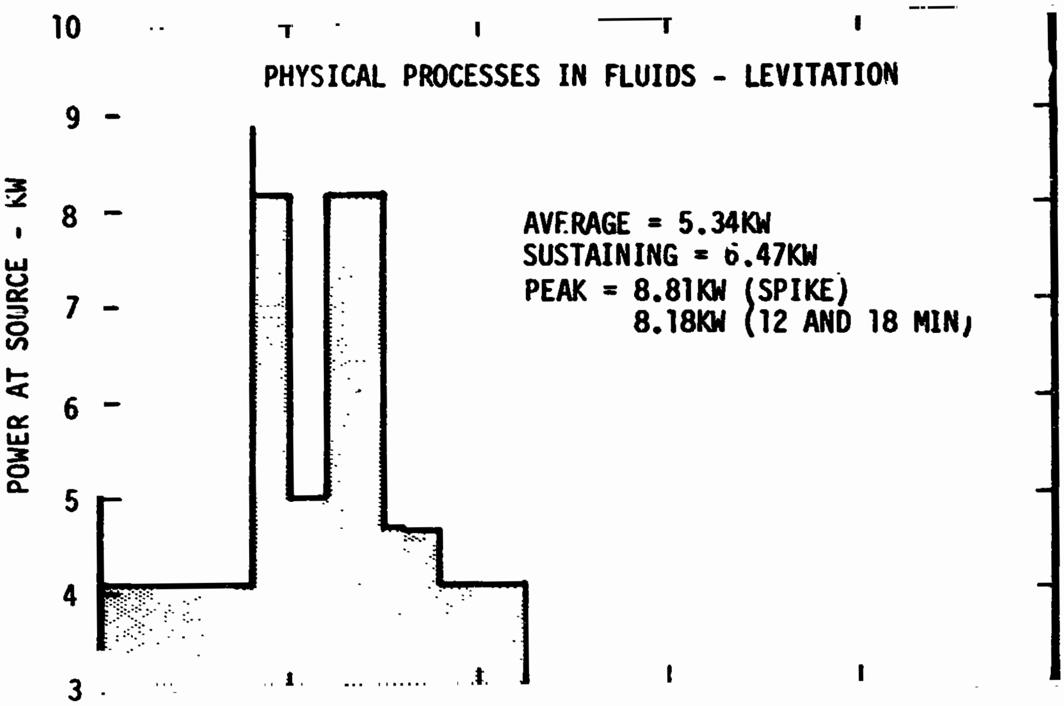


g. EXPERIMENT NO. 7

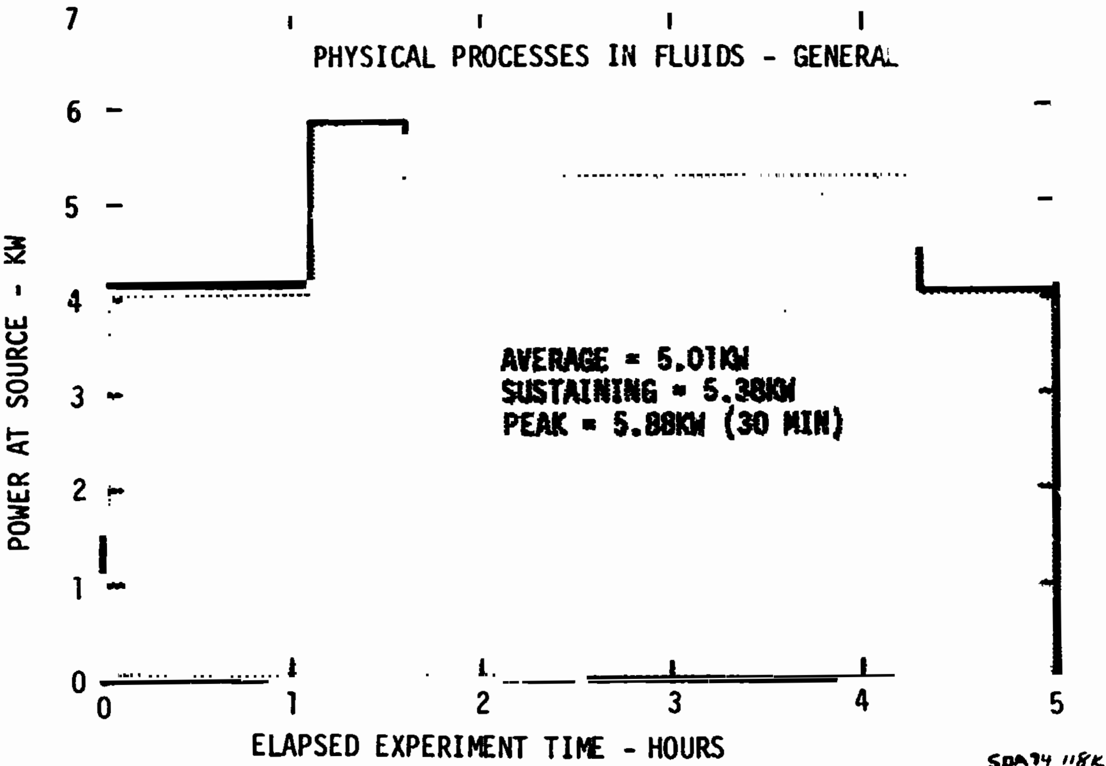


h. EXPERIMENT NO. 8

Figures 6g and h. SPA Experiment Power Source Load Profiles

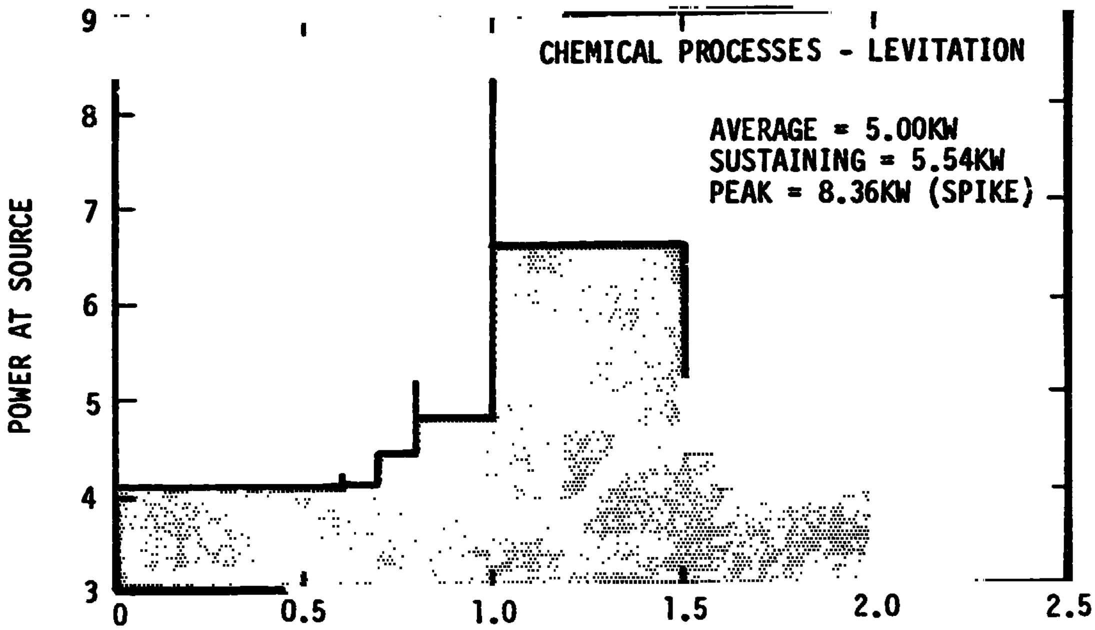


i. EXPERIMENT NO. 9

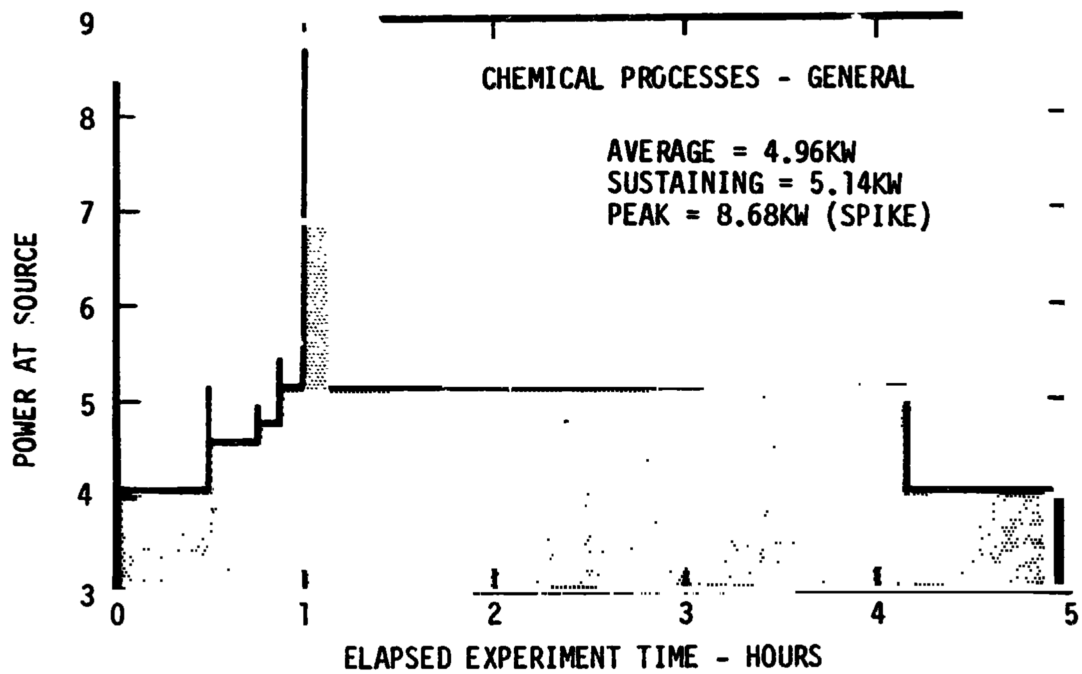


j. EXPERIMENT NO. 10

Figures 6i and j. SPA Experiment Power Source Load Profiles



k. EXPERIMENT NO. 11



1. EXPERIMENT NO. 12

SPA74-115L

Figures 6k and 1. SPA Exper.ment Power Source Load Profiles

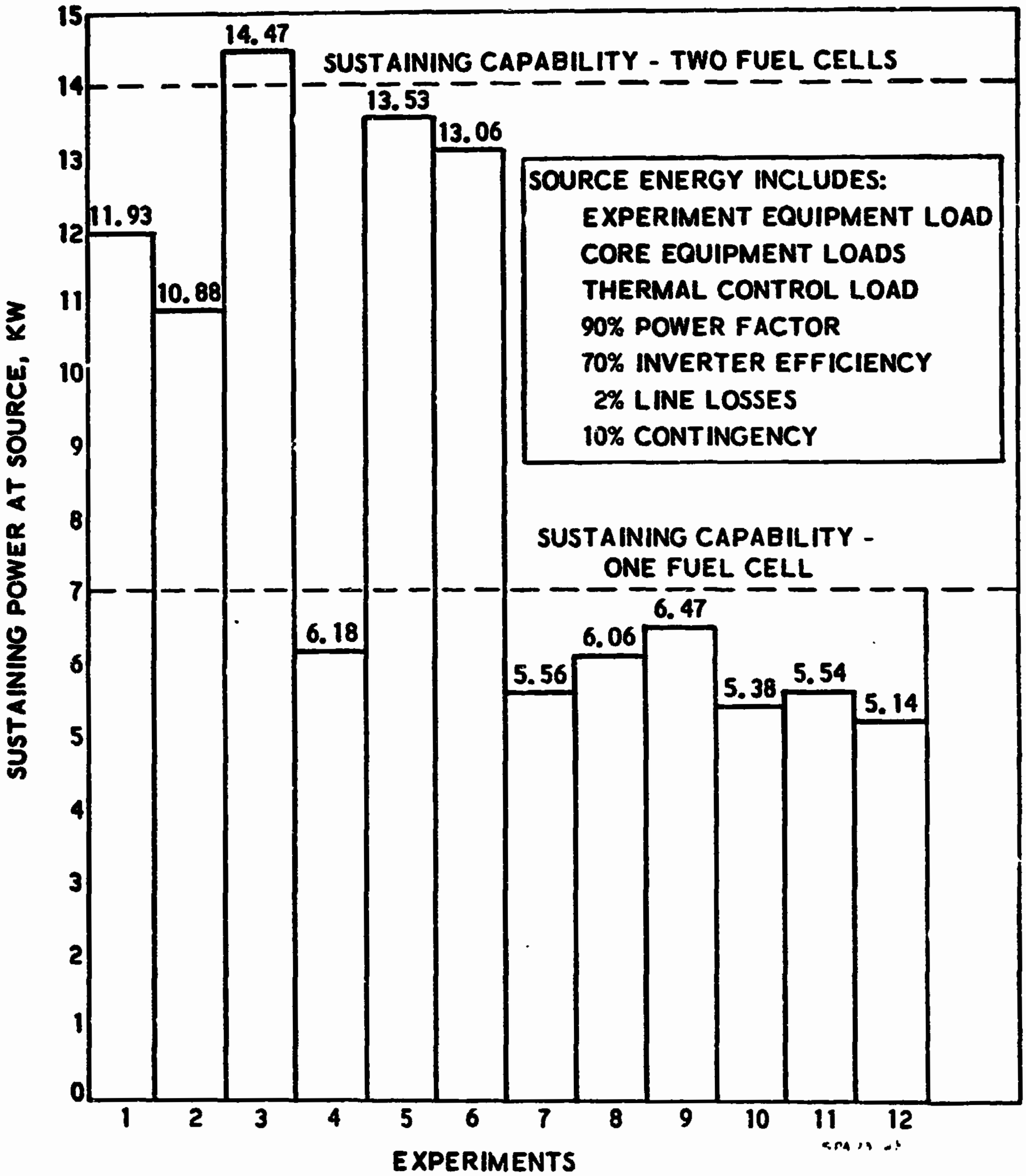


Figure 7. Sustaining Experiment Power (at Power Source)

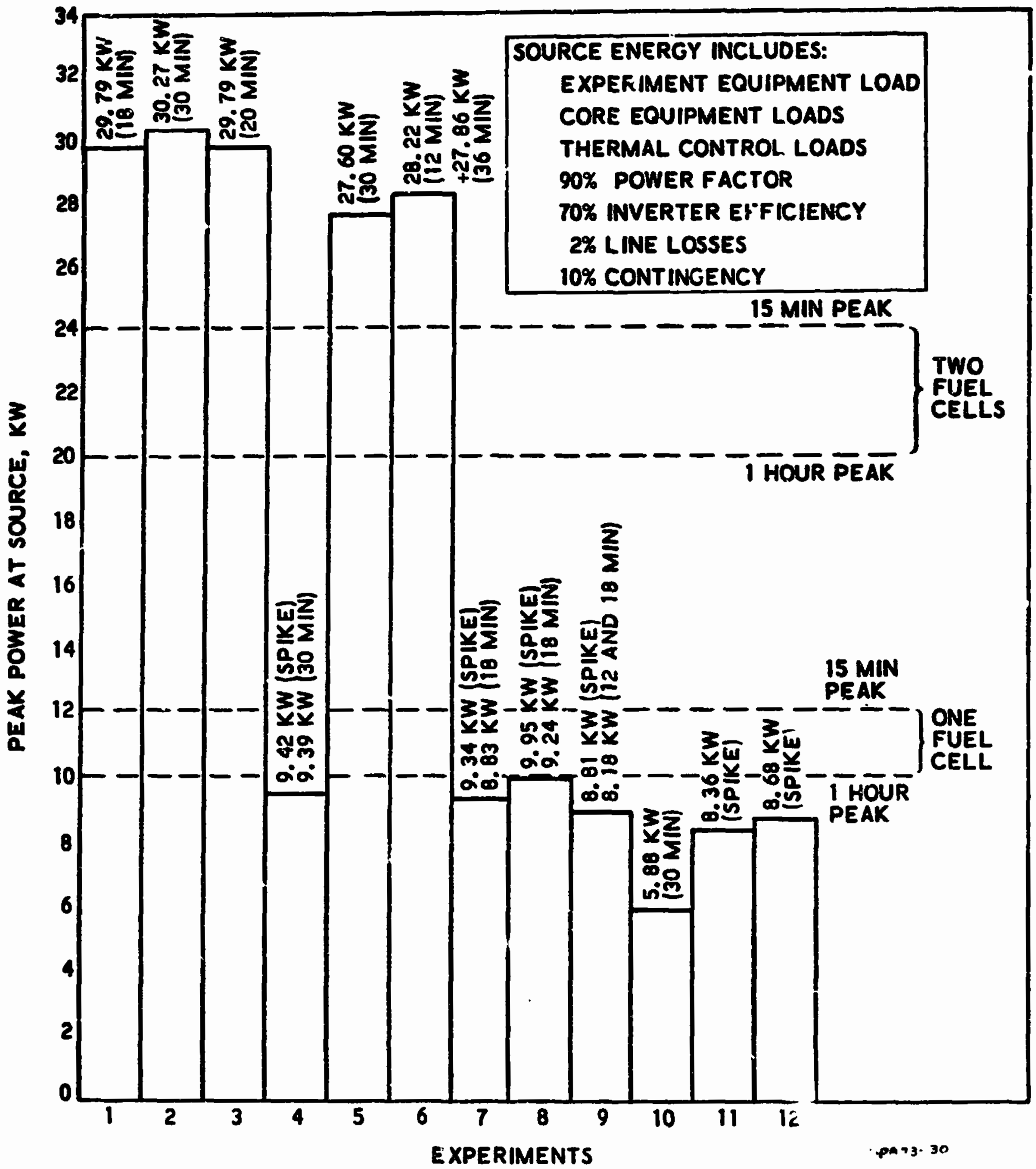


Figure 8. Peak Experiment Power (at Power Source)

The sustaining and peak experiment requirements at the power source were obtained in the same manner as the requirements illustrated in Section 3.1.1. The sum of the experiment equipment, the core subelement equipment, and the thermal control equipment requirements are reflected through the subsystem inefficiencies to obtain the values presented in Figures 7 and 8. The peak power requirements also show the duration of the peaks. For the case where more than one peak occurs that have similar magnitude, both peaks are shown. For the case where two identical peaks occur with a separation of only several minutes, the peaks are represented as one peak with a total duration equal to the sum of the duration of each peak.

The average values given are defined as the average power over the total elapsed experiment time for each experiment and occurs from turn-on of the core equipment (zero minutes). In Figures 6a and 6b, the duration used for the average power are 3.5 and 4.5 hours, respectively. The core equipment and thermal control equipment are on continuously during these durations and require slightly higher than 4 kW at the power source. The experiment equipment operates for a shorter period of time, and depending on the experiment, the sustaining power is the average power of all equipment during the shorter time duration.

The energy requirements for one cycle of each of the twelve experiments were also determined and these data are summarized in Figure 9. The energy requirements are at the energy source and include the total energy from turn-on to turn-off of the core and thermal equipment. The total energy requirement for a mission has not been determined, as it was not within the scope of this study; however, if mission experiment timelines of the twelve experiments were developed, the source energy requirements could be determined by multiplying the energy of a single cycle by the number of experiment cycles for each of the experiments used and combining the results. For example, if experiments 2, 4, 6, 8, 10, and 12 were used on a single mission and each required two cycles of operation, the total energy requirement would be as shown in Table 6.

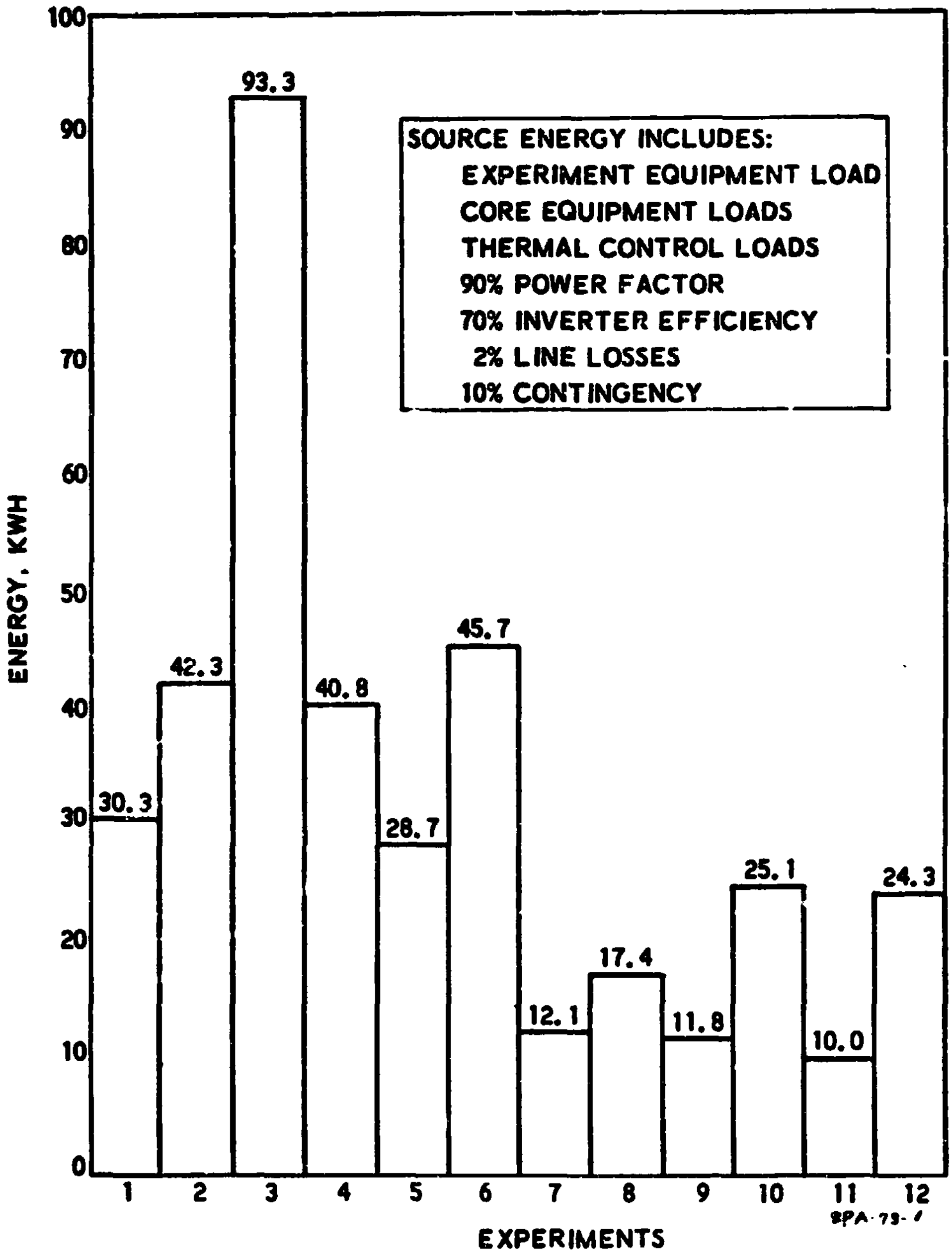


Figure 9. Experiment Energy Requirement at Power Source
(Energy per Experiment Cycle)

Table 6. Energy Calculation for Sample Mission

EXP	KWH/CYCLE	CYCLES	KWH/MISSION
2	42.3	2	84.6
4	40.8	2	81.6
6	45.7	2	91.4
8	17.4	2	34.8
10	25.1	2	50.2
12	24.3	2	48.6
			391.2 KWH

The energy data can also be used to determine the reactants required for the fuel cells and to determine the limits of experiments. For example, if Experiment 3 was part of the mission and 10 cycles were required, the total mission energy requirement would be 933 kWH. If only 950 kWH of power were available for the mission, then no other experiments could be considered unless additional reactants are provided.

3.2 POWER AVAILABILITY

To properly determine the electrical power requirements it is necessary to design and/or to know the characteristics of the electrical power source and then to relate the loads to the source. This section will define and describe the electrical power source, and summarize the experiment requirements at the source. The power conditioning and distribution losses are discussed in greater depth in Section 3.4.

3.2.1 Power Source Definition

The electrical power source that supplies electrical energy to the SPA experiments will be Shuttle type fuel cells. The fuel cells could be the Shuttle fuel cells, the Power/Heat Rejection Kit (see Section 3.3.2) fuel cells or both. Batteries may also be required for supplemental or peaking loads and the use of batteries could be designed to be compatible with the fuel cell output characteristics. Two different fuel cells are presently being considered for the Shuttle Orbiter and the one selected by NASA-JSC should be used for all applications so as to avoid duplication of development. Final selection of a fuel cell for Shuttle-Orbiter has not been made and the manufacturers are still in a competitive mode, thereby minimizing the availability of detailed data. Although the two

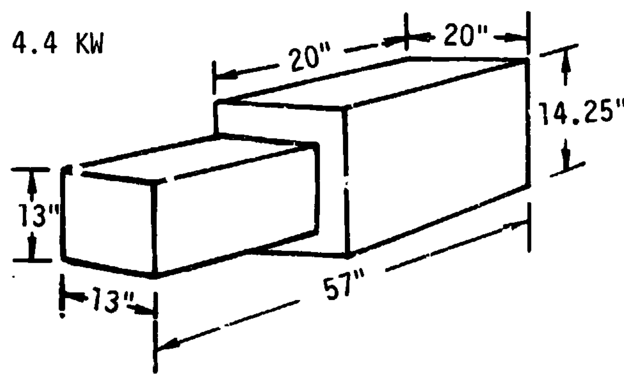
Table 7. Fuel Cell Performance

	Matrix	Ion Exchange
Vendor	P & W	GE
Electrolyte	KOH	Solid polymer
V_{oc} (per cell)	1.10 V	1.23 V
V_0 at rated load (per cell)	0.97 V	0.93 V
Cooling Method	Pumped liquid coolant plus open cycle H_2O boiling at backup	Pumped liquid coolant
Rated Output Power	7 kW	7 kW
Maximum Output Power	14 kW (with open cycle cooling)	14 kW (short duration)
Nominal current density	1300 amp/m^2 (120 amp/ft^2)	1400 amp/m^2 (130 amp/ft^2)
Stack Temperature	88°C (190°F)	82°C (180°F)
Reactant Inlet Pressure	420 kN/m^2 max (60 psia)	350 kN/m^2 max (50 psia)
Heat generated at rated load	4.4 kW	4.35 kW
Efficiency	61%	62%
Inherent Voltage Regulation (0.5 to 7.0 kW)	± 5%	± 5%
Short circuit current	3000 amp	800 amp
Weight	110 kg (245 lb)	146 kg (325 lb)
Specific Weight	16 kg/kW (35 lb/kW)	21 kg/kW (46 lb/kW)
Specific Reactant Consumption	0.4 kg/kWH (0.9 lb/kWH)	0.4 kg/kWH (0.9 lb/kWH)

SPA 74-11.1

NOTE: As of July 1974, it is understood that the P & W Fuel Cell has been selected.

Table 8. Shuttle Fuel Cell Characteristics

LIFE WITHOUT MAINTENANCE	2,000 HR MINIMUM 50 CYCLES (START-STOP) 9000 KWH
LIFE WITH MAINTENANCE	5,000 HR 125 CYCLES (START-STOP) 22,500 KWH
SHELF LIFE	10 YEARS
VOLTAGE	40 VOLTS (V_{oc}) 27.5 - 32.5 V_{dc} @ 2.0 TO 12.0 KW
POWER	2.0 TO 7.0 KW STEADY STATE UP TO 12 KW FOR 15 MINUTES UP TO 10 KW FOR 1 HR (EMERGENCY)
OVERLOAD	545 AMPS FOR 1 MINUTE MINIMUM
REACTANTS	GASEOUS HYDROGEN GASEOUS OXYGEN
PURGING	H_2 AND O_2 12 HOUR MINIMUM INTERVAL
REACTANT CONSUMPTION	0.9 LB PER KWH
HEAT GENERATED (RATED LOAD)	4.4 KW
SIZE ALL DIMENSIONS ARE MAXIMUM	
WEIGHT	245 LB (P & W) 325 LB (GE)
EFFICIENCY	61 - 62%
TEMPERATURE (OPERATING)	195° TO 230°F (90.6 TO 110.0°C) P & W 175° TO 200°F (79.5° TO 93.3°C) GE

SPA 74-115

types of fuel cells under development are required to meet a common specification, they differ in many respects, particularly in the type of electrolyte used. The latest available data will be presented. In most cases the worst case conditions of the known fuel cell characteristics were used for the analyses.

The two fuel cell types that are being considered for the Shuttle Orbiter are a matrix fuel cell proposed by Pratt and Whitney (P&W) and an ion exchange fuel cell under development by General Electric (GE). Each of the fuel cell electrical power generating systems contain the fuel cell stack, valves and plumbing for reactant control, a coolant pump, water separator, and heat exchanger. The design nd performance characteristics of both fuel cell types are summarized in Table 7 (References 4 and 6).

More detailed and up-to-date characteristics of the fuel cells are contained in Reference 2, 3 and 5. A summary of these characteristics are contained in Table 8. It is apparent that some of these characteristics are still changing but not significantly. Selection of a fuel cell manufacturer should result in firmer characteristics. The characteristics shown were used in the design of the Power/Heat Rejection Kit and for the thermal control interface designs discussed in Sections 3.3.2 and 3.5. Each of these sections contain additional data on the fuel cell generating system and is relative to their design.

3.2.2 Power Source Accommodation Analysis

The Shuttle Orbiter will provide electrical power from its three fuel cells in support of the Orbiter and the Spacelab operations. One of the three Shuttle Orbiter fuel cells is dedicated to the Spacelab electrical power requirements during normal Shuttle operation. Each fuel cell has a capability of providing from 2.0 to 7.0 kW continuously with peak capability of up to 12.0 kW for 15 minutes. This power supplies the Spacelab subsystems and the excess is available to the payload. A summary of these capabilities and their characteristics are shown in Table 9. The normal energy available from the Orbiter is 50 kWH, however, an additional 900 kWH can be provided by the Orbiter, but the reactant and tankage weights are charged to the Spacelab or the SPA payload.

The current Spacelab subsystem requirements result in a payload allocation of 4.0 to 4.8 kW average and 9.0 kW peak. The average power is a 24 hour/day average and the peak is a 15 minute maximum duration peak with a minimum separation of 3 hours between peaks. (Reference 1).

Table 9. Orbiter Power Availability to Payload

	AVERAGE	PEAK
POWER, KW		
LAUNCH	1.0	1.5
ON-ORBIT NORMAL OPERATIONS	7.0	12.0
ON-ORBIT DEGRADED OPERATIONS	5.0	8.0
REENTRY	1.0	1.5
VOLTAGE, VOLTS - DC		
CONTINUOUS DUTY	24 TO 32	
INTERMITTENT DUTY	23 TO 32	
RIPPLE	4 (PEAK TO PEAK)	
ENERGY, KWH	950	
SPACELAB PAYLOAD ALLOCATION, KW		
MODULE ONLY	4.0	9.0
MODULE AND PALLET	4.8	9.0
PALLET ONLY	4.8	9.0
PALLET ELEMENT	1.5	2.0
ENERGY ALLOCATION, KWH		
MODULE ONLY	595	
MODULE AND PALLET	595	
PALLET ONLY	730	

Additional power sources may be provided to supply electrical power requirements that exceed the allocation of electrical power from the Orbiter. The power sources considered were supplemental and/or peaking battery kits (see Section 3.3.1) and the use of a Power/Heat Rejection Kit that will contain up to two Shuttle-type fuel cells and the necessary plumbing, controls, reactants and tankage to satisfy the SPA experiment requirements (see Section 3.3.2). The Power/Heat Rejection Kit would provide up to 14 kW of continuous power and peaks of up to 24 kW for 15 minutes. For purposes of this analysis the emergency peaking of 10 kW per fuel cell or 20 kW total for one hour was also assumed.

The use of the experiment payload allocation from the Orbiter and the Power/Heat Rejection Kit will provide electrical power to the SPA experiments of from 4.0 to 18.8 kW continuously and peaks of up to 33 kW for 15 minutes. The Spacelab electrical power requirements to support its subsystems are not fixed and any increase in these requirements will result in decreases in the power available to the experiments.

For the purpose of assessing the capability of the electrical power allocations to satisfy the SPA experiment requirements, the sustaining and peak experiment electrical power requirements at the source for each of the 12 identified experiments (See Figures 7,8 in Section 3.1.3) were compared with the power allocations from the Spacelab and the Power/Heat Rejection Kit.

The sustaining and peak power requirements for each of the twelve experiments are relatively high. This fact is partially attributed to the commercial equipment designers that have lacked concern about power consumption. Also, the electrical load analyses conducted during this study are based upon typical equipment and some worst-case conditions. When a decision was required under the above conditions, a worst-case or near-worst-case condition was usually selected. A refinement or scrubbing of the experiment equipment requirements and time lines and possible increases in power conditioning efficiencies by identifying equipment that does not require regulated sine wave AC could result in some decrease in the power requirements.

The sustaining and peak SPA experiment electrical power requirements at the source were compared to the average and peak electrical power

allocations to the SPA experiment from the Shuttle Orbiter/Spacelab and from the Power/Heat Rejection Kit as shown in Table 10. The "X's" on the table indicate that the allocation concept's average or peak power capabilities satisfy the sustaining or peak power requirements, respectively, of that experiment. The Spacelab allocation provided by the Concept 1 configuration of 4 to 4.8 kW average does not satisfy any of the 12 SPA experiment sustaining power requirements, although five of the experiments peak power requirements are satisfied by the 9 kW peak allocation. The use of a Power/Heat Rejection Kit with one fuel cell (Concept 2), 7 kW average and 12 kW for 15 minutes, satisfies both the sustaining and peak requirements of seven of the twelve SPA experiments. Concepts 1 and 2 were combined to obtain Concept 3 to give an average capability of 11 to 11.8 kW and 21 kW peak. This concept appears to offer no significant advantage over Concept 2 as the sustaining power requirement of only one additional experiment if only one additional experiment is satisfied. A two-fuel-cell Power/Heat Rejection Kit with a 14 kW average and a 24 kW for 15 minute capability (Concept 4) satisfies eleven of the twelve SPA experiment sustaining power but only seven of the SPA experiment peak power requirements. All of the experiments sustaining and peak power requirements are satisfied by the average capability of 18 to 18.8 kW and peak capability of 33 kW for 15 minutes for Concept 5.

To perform all of the twelve identified SPA experiments requires a two-fuel-cell Power/Heat Rejection Kit in addition to the Spacelab experiment allocation. A significant increase in the Spacelab subsystem requirements could result in a significant decrease in the power allocated to the experiments from the Spacelab and Concept 5 would not be able to satisfy all of the experiment requirements. If the experiment allocations as indicated in Table 10 are derated, then the resultant number of experiments that can be operated is decreased. Without the Power/Heat Rejection Kit none of the experiments are fully satisfied.

For purposes of satisfying the experiment requirements with derated power allocations it is apparent that the use of supplemental and/or peaking batteries would be necessary. The energy required to supplement each concept and to satisfy each experiment are listed in Table 11. Conceivably, if only the power from the Power/Heat Rejection Kit (Table 10,

Table 10. SPA Experiment Power Source Accommodation

EXPERIMENT NO.	EXPERIMENT NAME	POWER SOURCE CONCEPTS: 1 SPACE LAB ALLOCATION ONLY[1]		2 POWER-HEAT REJECTION KIT[2] ONE FUEL CELL		3 SPACE LAB ALLOCATION PLUS POWER-HEAT REJECTION KIT ONE FUEL CELL		4 POWER-HEAT REJECTION KIT TWO FUEL CELLS		5 SPACE LAB ALLOCATION PLUS POWER HEAT REJECTION KIT TWO FUEL CELLS	
		AVERAGE 4 TO 4.8 KW	PEAK 9 KW	AVERAGE 7 KW	PEAK 12 KW[3]	AVERAGE 11 TO 11.8 KW	PEAK 21 KW	AVERAGE 14 KW	PEAK 24 KW	AVERAGE 18 TO 18.8 KW	PEAK 33 KW
1	METALLURGICAL - FURNACE							X		X	X
2	METALLURGICAL - LEVITATION					X		X		X	X
3	CRYSTAL GROWTH - FURNACE									X	X
4	CRYSTAL GROWTH - LEVITATION			X	X	X	X	X	X	X	X
5	GLASS TECHNOLOGY - FURNACE							X		X	X
6	GLASS TECHNOLOGY - LEVITATION							X		X	X
7	BIOLOGY APPLICATIONS - STATIONARY COLUMN *		X	X	X	X	X	X	X	X	X
8	BIOLOGY APPLICATIONS - CONTINUOUS FLOW			X	X	X	X	X	X	X	X
9	PHYSICAL PROCESSES IN FLUIDS - LEVITATION		X	X	X	X	X	X	X	X	X
10	PHYSICAL PROCESSES IN FLUIDS - GENERAL		X	X	X	X	X	X	X	X	X
11	CHEMICAL PROCESSES - LEVITATION		X	X	X	X	X	X	X	X	X
12	CHEMICAL PROCESSES - GENERAL		X	X	X	X	X	X	X	X	X

SPA 77-31

NOTE:
1. SPACELAB SUBSYSTEM SPECIFICATION, ISSUE 3, REVISION 2, ESRO, 1973 OCTOBER 15.
2. FUEL CELL POWERPLANT, PROCUREMENT SPECIFICATION, MC464-0115, SPACE DIVISION, NAR, 1973 MAY 10.
3. PEAK POWER CAPABILITY IS 12 KW for 15 MIN AND 10 KW FOR ONE HOUR PER FUEL CELL.

*Indicates that the allocation concepts average or peak power capabilities satisfy the sustaining peak power requirements, respectively, of the experiment.

Table 11. Additional SPA Experiment Energy Requirements
(Kilowatt-Hours per Experiment Cycle)

EXPERIMENT NO.	EXPERIMENT NAME	POWER SOURCE CONCEPTS									
		1		2		3		4		5	
		AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK
1	METALLURGICAL - FURNACE	14.26-15.86	10.81	9.86	8.54	0.26-1.86	2.71	-	1.82	-	-
2	METALLURGICAL - LEVITATION	21.08-23.85	17.59	13.45	15.31	-	5.22	-	4.30	-	-
3	CRYSTAL GROWTH - FURNACE	59.22-64.02	59.73	46.02	46.34	17.22-22.02	3.06	4.02	2.08	-	-
4	CRYSTAL GROWTH - LEVITATION	7.94-12.84	1.02	-	-	-	-	-	-	-	-
5	GLASS TECHNOLOGY - FURNACE	12.51-13.66	12.84	9.36	8.80	2.47-3.62	3.88	-	2.46	-	-
6	GLASS TECHNOLOGY - LEVITATION	24.78-27.18	25.84	18.18	15.07	3.78-6.18	7.42	-	5.24	-	-
7	BIOLOGY APPLICATIONS - STATIONARY COLUMN	1.60-3.28	-	-	-	-	-	-	-	-	-
8	BIOLOGY APPLICATIONS - CONTINUOUS FLOW	3.53-5.75	0.09	-	-	-	-	-	-	-	-
9	PHYSICAL PROCESSES IN FLUIDS - LEVITATION	1.67-2.47	-	-	-	-	-	-	-	-	-
10	PHYSICAL PROCESSES IN FLUIDS - GENERAL	1.91-4.55	-	-	-	-	-	-	-	-	-
11	CHEMICAL PROCESSES - LEVITATION	0.74-1.54	-	-	-	-	-	-	-	-	-
12	CHEMICAL PROCESSES - GENERAL	1.26-4.22	-	-	-	-	-	-	-	-	-

NOTE:
1. BLANKED OUT AREAS INDICATE THAT REQUIREMENTS SATISFIED BY POWER SOURCE CONCEPT.
2. KWH VALUES CAN BE USED TO SIZE SUPPLEMENTAL OR PEAKING BATTERIES.

Concept 4) were available, batteries could be used to supplement the sustaining requirement of Experiment 3 and provide the peaking requirements of Experiments 1, 2, 3, 5 and 6. For each additional experiment cycle the energy values must be multiplied by the number of cycles. This approach can be employed to determine the energy requirement for each concept. The dashed lines presented in Table 11 indicate those requirements that have been satisfied by the concept.

The type and size of batteries are beyond the scope of this study and have not been determined at this time, but further discussion can be found in Section 3.3.1. The size and type of battery are dependent upon the experiment, mission and end use of the batteries. Supplemental battery, peaking battery and power source concept tradeoffs can be performed when mission timelines are established for the SPA discipline.

3.3 POWER KITS EVALUATION AND REQUIREMENTS

As previously discussed, supplemental and/or peaking electrical power sources are required to satisfy the SPA experiment electrical power requirements. This power can be provided by kits. Two types of kits have been considered: (1) a battery kit for supplemental and/or peaking requirements, and (2) a Power/Heat Rejection Kit for supplemental power requirements.

3.3.1 Battery Kit

One method of providing the additional supplemental and peaking power requirements of the SPA experiments is the use of a battery kit. The battery kit could be comprised of as many batteries as required to satisfy the supplemental or peaking requirements. The batteries are connected to a battery bus which is, in turn, connected to the load bus (either to the Spacelab or experiment bus). Battery chargers, necessary control and protection electronics are required with the use of secondary batteries so as to assure a safe system. A battery kit concept is depicted in Figure 10.

Batteries could be required for several applications. The most apparent use of batteries is to satisfy the sustaining and peak power requirements of the experiments when the Spacelab experiment allocation and/or the Power/Heat Rejection Kit capability does not satisfy the experiment sustaining or peak power requirements. These requirements are

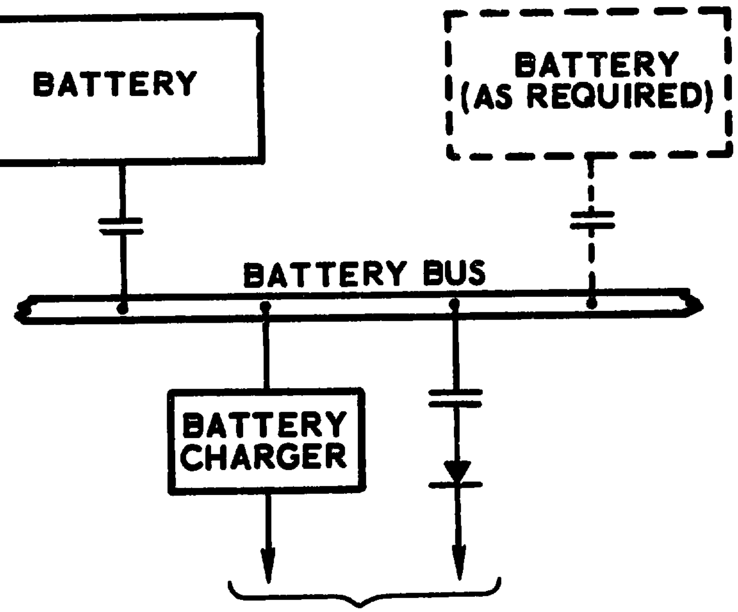


Figure 10. Typical Battery Kit (Peaking and Supplemental Power)

presented in Table 11 in Section 3.2.2 as the average and peak requirements per experiment cycle for several concepts. In most cases the use of a secondary (rechargeable) battery would be required because of the high energy requirements. The battery would be recharged during low power periods and reused, however, the total energy from the fuel cells would also have to include the energy required to recharge the battery. This would result in a slightly higher total energy when compared to the condition whereby the fuel cells provided the total power requirement. The return factor for recharging the battery is 110 to 130% of the ampere-hours taken out.

Another application for batteries is to assist the fuel cells during those conditions when large instantaneous increases in power are required. Although the fuel cell transient response is relatively fast over its design range (Reference 2), the use of peaking batteries may be desirable. The large increases in power requirements can be seen in the experiment power source load profiles in Figures 6a-l (Section 3.1.3). There are at least four experiments that have instantaneous increases of over 20 kW and all experiments have at least one instantaneous increase of from 1.7 to 6.8 kW. Further analyses are required to determine battery requirements as they relate to fuel cell characteristics and capabilities, and the possibility of programming the experiment equipment as a means of reducing large instantaneous changes.

The battery types that are considered for the battery kit are rechargeable nickel-cadmium or silver-zinc and primary silver-zinc. Several of the advantages and disadvantages of each of the three battery types are summarized in Table 12. The nickel-cadmium secondary batteries have a proven long life capability through extensive testing and operation in space environments. They have been used on many U. S. satellites and space vehicles. These batteries have a reliable recharge capability and can be recharged between peaks and/or during low power requirement periods. Silver-zinc secondary batteries have a higher energy density when compared to nickel-cadmium but have a much shorter cycle life capability and must be recharged at lower rates. Silver-zinc primary batteries have the highest energy density but have essentially no recharge capability (several cycles only) and would have to be replaced after each mission.

Silver-zinc batteries have been used in space principally (Apollo program) where several capacities including large capacity batteries were used. One major disadvantage of silver-zinc batteries are their relatively short shelf life characteristics, however, this factor may not be a problem for the SPA experiment mission.

Table 12

Battery Kit - Battery Types

Nickel-Cadmium (Ni-Cd) secondary
- Long cycle life
  - 1,000's of cycle-function of depth of discharge
- Proven Operational Testing
  - Most satellites and extensive lab testing
- Good recharge capability
- No replacement after each mission
- Recharge between peaks - during low requirement periods

Silver-Zinc (Ag-Zn) secondary
- Higher energy density than Ni-Cd
- About 200 cycles
- Replace after one or two missions
- Charge at lower rates than Ni-Cd
  - Therefore longer charge time is required

Silver-Zinc (Ag-Zn) primary
- High energy density
- Essentially no recharge capability
- Replace after each mission

3.3.2 Power/Heat Rejection Kit

A Power/Heat Rejection Kit attached to the Spacelab offers a solution to satisfy the SPA experiment power and thermal control requirements. The structural detail of the kit and concepts for equipment storage are shown and discussed in Volume II-D. The electrical power portion of the kit and its interfaces will be discussed in this section. Both fuel cells and auxiliary power units (APU's) were considered for the kit and both will be discussed in this section, however, the APU's are not compatible for this mission.

The electrical power subsystem of the Power/Heat Rejection Kit is made up of two fuel cells, oxygen and hydrogen reactant tank assemblies, water storage tanks, plumbing, cabling and inverters to convert the nominal 28 V DC fuel cell output to AC power. A simplified block diagram

of the electrical power subsystem is presented in Figure 11. The power conditioning and distribution elements of the kit are discussed in Section 3.4. The electrical power system has an output from both fuel cells of approximately 14 kW average with peaks of up to 24 kW for up to a 15 minutes' duration. Higher peaks can be sustained for shorter periods of time and lower peaks for longer periods. The fuel cells have an emergency capability (Reference 2) of 10 kW for one hour, and this level was assumed for this study. The reactant tank assemblies provide for cryogenic storage of hydrogen and oxygen to provide about 1000 kWH of energy.

A flow diagram of a fuel-cell power plant is presented in Figure 12 and is a simplified diagram that is based upon the Shuttle Orbiter's design of the fuel-cell (Reference 5). The subsystem is comprised of two fuel cells with their interfaces tied together as shown. The fuel-cell power plant's interfaces are: (1) the oxygen and hydrogen reactant inlets, (2) vents for oxygen and hydrogen purge and water, (3) coolant inlet from an outlet to a thermal control heat exchanger, and (4) the principal outputs of electrical power to the loads and by-product water to storage tanks.

Oxygen and hydrogen are supplied to the fuel cell's inlet where the reactants are heated within the power plant before entering the cell stack. The electrical power is generated by electrochemical reaction of oxygen and hydrogen. The electrical power is delivered to the equipment loads through power conditioning and distribution elements. This reaction has an efficiency of about 60%, resulting in the generation of heat which is carried away by the coolant loop. The coolant passes through the thermal control heat exchanger where the thermal control subsystem picks up the heat for dissipation. The water is collected in special storage tanks and used as needed to satisfy additional thermal control requirements. The water is not dumped because of the thermal control requirements and the fact that it can potentially be used to maintain the vehicle's center of gravity (c.g.). The water tanks are sized to store all of the water that is produced by the fuel cells and not required by the thermal control subsystem. The fuel cell's stack is purged at minimum intervals of 12 hours by hydrogen and oxygen.

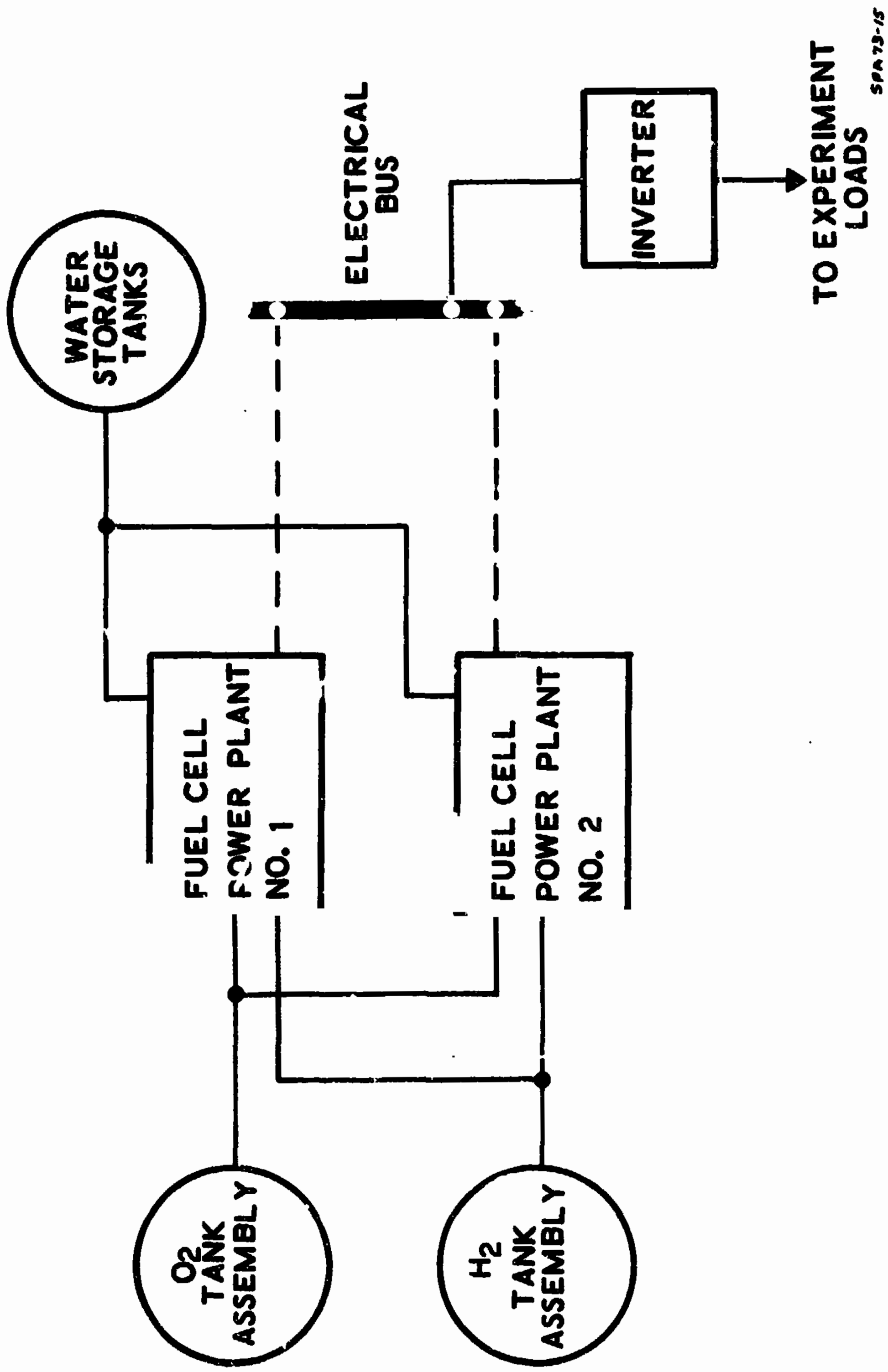


Figure 11. Fuel Cell Electrical Power Subsystem

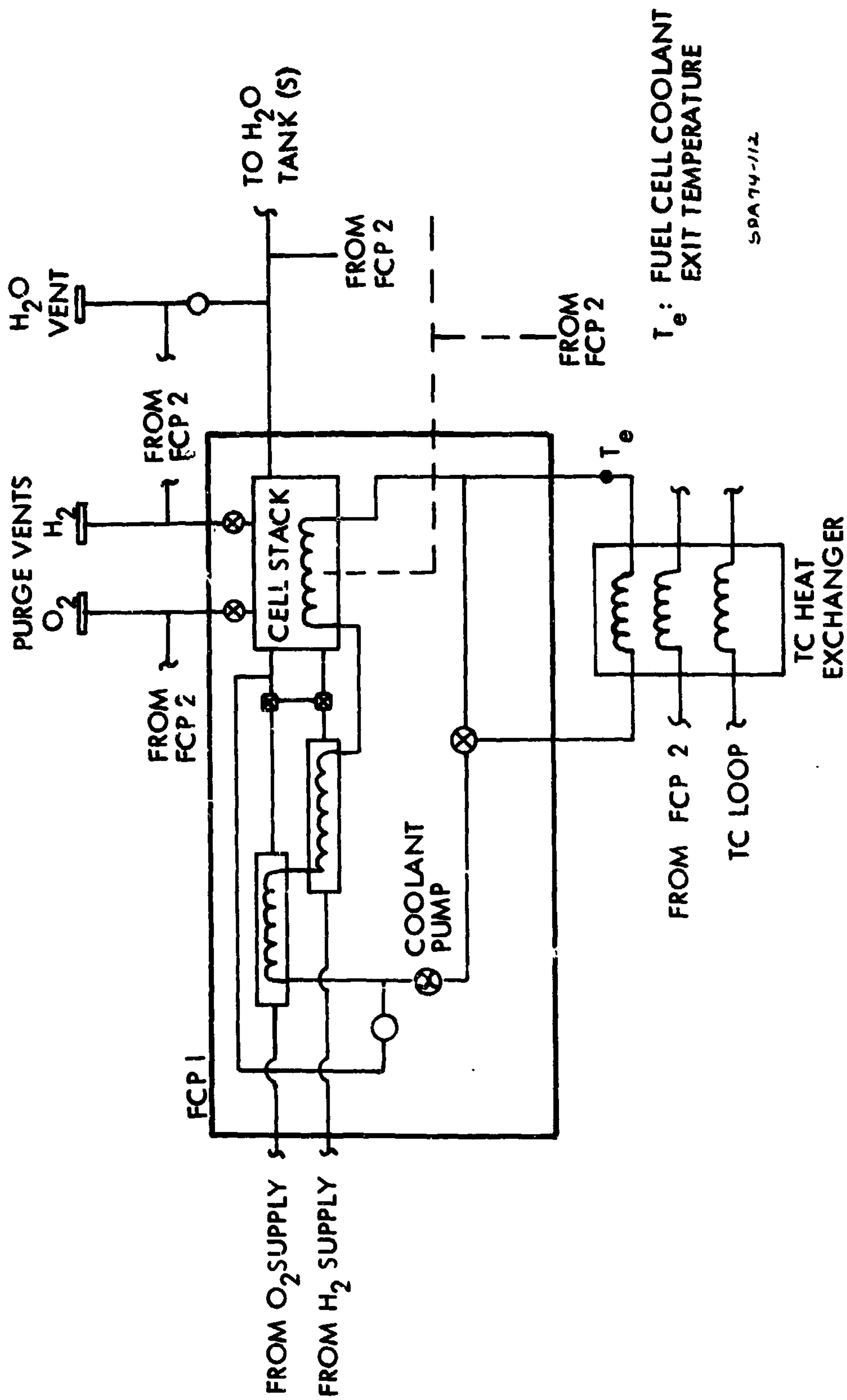


Figure 12. Fuel Cell Power Plant (FCP)

Each power plant is capable of providing 27.5 to 32.5 volts of DC power over a power range of 2 to 12 kW for 15 minutes. The design goal for the power plants' operational life without maintenance is 2,000 hours and is 5,000 hours with maintenance. This includes 50 start/stop cycles with no maintenance and 125 start/stop cycles with maintenance.

The source of energy for the fuel cells is provided by supercritical cryogenic storage dewars that supply oxygen and hydrogen to the fuel-cell power plants. The reactants are maintained at a pressure greater than the fluid-critical pressure and reactants are supplied in a single fluid state by simple pressure feed. The nominal pressure of 1.7 MN/m^2 (250 psia) for hydrogen and 6.2 MN/m^2 (900 psia) for oxygen is maintained by supplying heat to the fluid when the pressure in the dewars drops below a minimum allowed pressure limit. The reactant tank assembly for the Power/Heat Rejection Kit is presented in Figure 13. The tank assemblies include the heaters, pumps, filters, valves and control loops necessary to maintain storage and to supply the reactant to the power plants. The interfaces for fill, drain, vent and supply are also shown. The Power/Heat Rejection Kit is comprised of one or more various combinations of the oxygen and hydrogen tank assemblies.

The performance characteristics of the Power/Heat Rejection Kit is designed to satisfy the sustaining and peak power requirements of the SPA experiments as presented in Section 3.1.2.

To power hydraulic pumps during prelaunch, ascent, entry and landing, the Shuttle orbiter uses four independent, 130 horsepower, monopropellant, hydrazine auxiliary power units (APU's). The possible use of these units has been considered as a supplemental power source for the SPA experiments. The performance characteristics of each APU is presented in Table 13.

Table 13

Auxiliary Power Unit (APU) Characteristics

(Shuttle Orbiter)

Rating	~97 kW (130 hp)
Propellant	Hydrazine (N_2H_4)
Starting	Bootstrap, Pump Fed
Turbine	60,000 to 80,000 RPM
SPC	2.2 to 4.4 lb/kWH

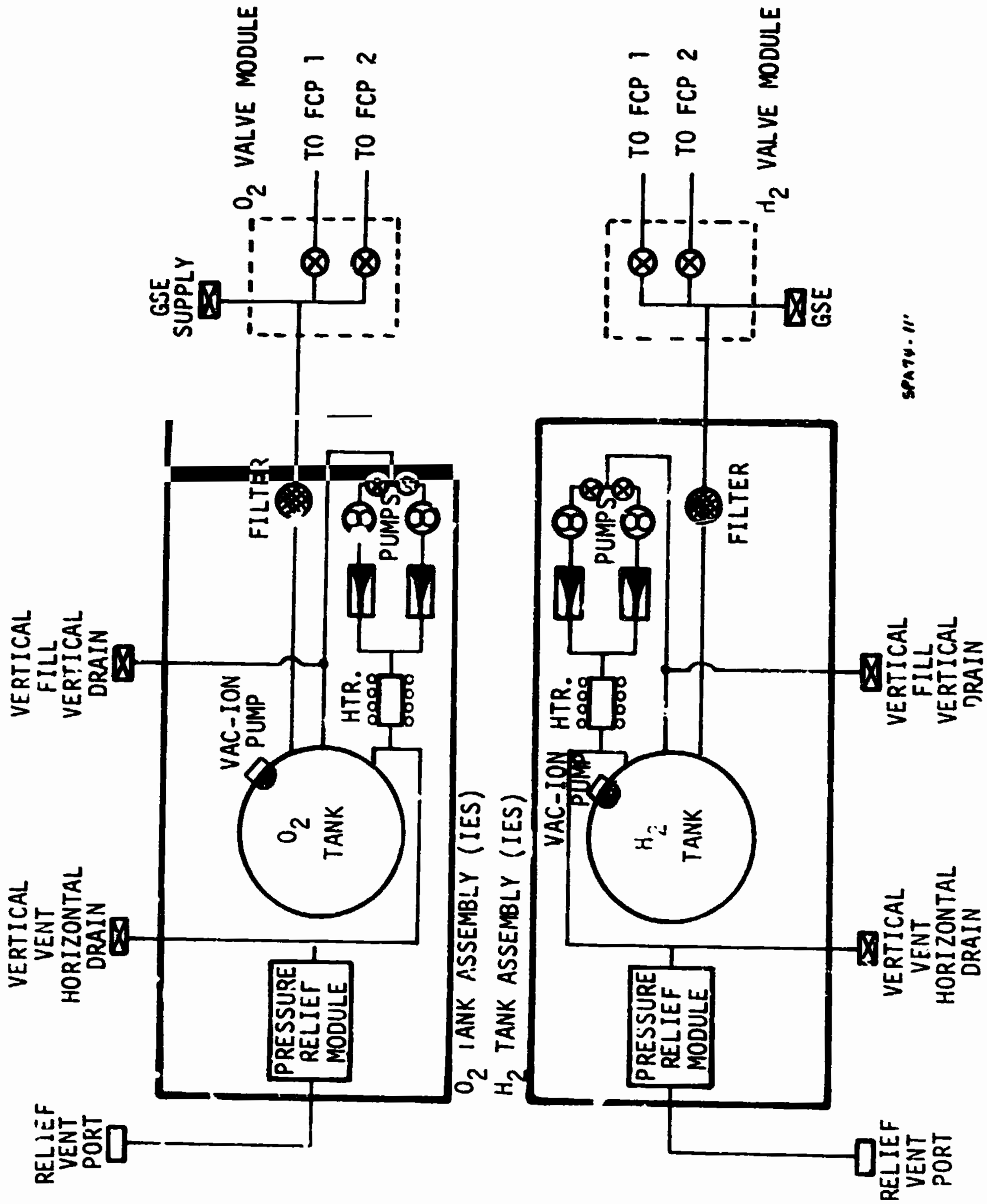


Figure 13. Power Reactant Storage Tank Assembly

It is conceivable that the APU could drive a generator and deliver AC power directly. Their hardware weight per kW is less than that of fuel cells. However, the size of the orbiter APU's, 130 hp or approximately 97 kW, could create difficulties in controlling the proper speed to generate 60 to 400 Hz power. The reactant consumption is greater than twice that of fuel cells and the high speed dynamic units result in noise and vibration that is incompatible with the experiments. The orbiter APU's are shut down on attainment of orbit and the use of APU's are not considered for the Spacelab SPA experiment application.

3.4 POWER CONDITIONING AND DISTRIBUTION

The electrical power distribution subsystem addresses SPA payload design problems dealing with power processing, distribution and control as it emanates from the power source (fuel cells) to selected experimental equipment.

The electrical distribution subsystem provides the following functions to the electric power subsystem interface:

- Power switching and distribution to all experiments
- Signal distribution
- Signal conditioning
- Interconnection of all electrical interfaces

The power distribution subsystem will be constrained in design by the following factors:

- The 28 V DC fuel cell bus shall be protected by DC circuit breakers
- The DC-AC inverters are to be self-protecting for overvoltage on the input as well as overload and short circuit of the output.
- The low power output feeder lines (500 amp) shall be protected by AC circuit breakers.
- The higher power output feeder lines shall be protected by fault detectors which will clear the faulted bus. Circuit breakers are not practical on the higher power buses because insufficient overload current is available to trip the breakers, since the source is a current limited inverter.

3.4.1 Concepts and Alternatives

The electrical power distribution subsystem takes the available source power and distributes this power to the experimental equipment in a safe

and efficient manner. The following distribution systems were considered:

- 28 VDC distribution system
- 60 Hz AC distribution system
- 400 Hz AC distribution system
- 1600 Hz AC distribution system

3.4.2 Evaluation and Comparison

The electrical power distribution subsystem selected for the Spacelab experiment equipment should interface with the commercially available experiment equipment with a minimum of modification.

The experiment equipment selected for the Spacelab mission are commercially available units operating from a 115 V 60 Hz or 400 Hz bus. The majority of the units are rated for a 60 Hz bus, but with minor modifications, can be adapted to operate off of a 400 Hz or higher frequency bus.

For high power experiment loads requiring precise power control, a higher frequency system is desirable. With a low frequency system, proportional control (phase control) is required to obtain the regulation accuracy whereas with a higher frequency system, zero switching control can be utilized. Proportional control of high power loads result in high electromagnetic interference (EMI) being generated since switching occurs during a cycle.

The 115 VAC at 400 Hz is selected for the low power experiment bus for the following reasons:

- Lower cabling weight than 28 VDC
- Minor or no modification required on experiment equipment
- Voltage level can be changed readily by transformers
- Availability of circuit breakers
- Airborne qualified and specified by MIL-STD-704

The 115 VAC, 3 phase (Ø), 4 wire at 1600 Hz or 1800 Hz is selected for the high power experiment bus.

Table 14 provides a tradeoff in size and weight for DC to AC inverters for 60 Hz, 400 Hz and 1800 Hz.

Table 14

DC to AC Inverter Size and Weight Comparison

Freq, Hz	Output, VA	Weight kg (lb)	Weight/Unit Output kg/VA (lb/VA)	Dimensions, cm (in)	Volume/Unit Output cm^3/VA (in^3/VA)
60	1500	65.8 (145)	0.045 (0.10)	43.8 x 39.6 x 26.6 (17-1/4 x 15-9/16 x 10-1/2)	30.7 (1.87)
400	1500	52.2 (115)	0.03 (0.07)	43.8 x 39.6 x 26.6 (17-1/4 x 15-9/16 x 10-1/2)	30.7 (1.87)
1800	18000	22.7 (50)	0.013 (0.028)	48.2 x 55.9 x 175 (19 x 22 x 69)	26.2 (1.60)

3.4.3 Concept Selection

The electrical distribution subsystem will be limited to the power sources and requirements that are available to the Spacelab from the Shuttle and any onboard primary or secondary sources of power as designated by the electrical power subsystem. The baseline power distribution selected for Space Processing is an AC system that utilizes 400 Hz, single-phase inverters for low power and 1800 Hz or 1600 Hz, three-phase; 4-wire inverters for high level power. An additional design constraint for power distribution is that manual switching be considered as baseline for the system. All power and signal distribution will consider the impact of electromagnetic interference and that sufficient safeguards be made available to minimize the effects of short circuits at one load from influencing other experiments.

Figure 14 presents a block diagram of the power distribution system. Two isolated 28 VDC primary power buses provide the power requirements for the experiment loads of the Spacelab.

Power conversion from 28 VDC to 400 Hz and 1800 Hz AC is accomplished by static DC to AC inverters. For the 400 Hz distribution bus, four 1500 VA inverters are connected in parallel. The inverters are frequency and phase synchronized to prevent dynamic interactions and system instability. Each of the 1500 VA inverters can be further divided into smaller VA rating inverters for redundancy considerations. The 1800 Hz, 3-phase inverter shown as a single block can be made up of several inverters connected in parallel. When considering safety aspects of the system, the inverters are self protecting for overvoltage on the input as well as overload and short circuit of the output.

A variety of switches and sensors are needed for load and inverter ON/OFF control, for protection of the primary buses and for removal of faulty loads and inverters. The input power junction box contains circuit breakers and fault sensors for inverter input power protection and switchi . Circuit breakers can be used on low VA rated inverters since enough overload current is available from the bus to trip the breaker. As the VA rating of the inverter approaches the VA rating of the bus, circuit breakers will not be able to clear a fault and other means of fault isolation must be used. A fault detector which senses both voltage and current is therefore used on all high power applications.

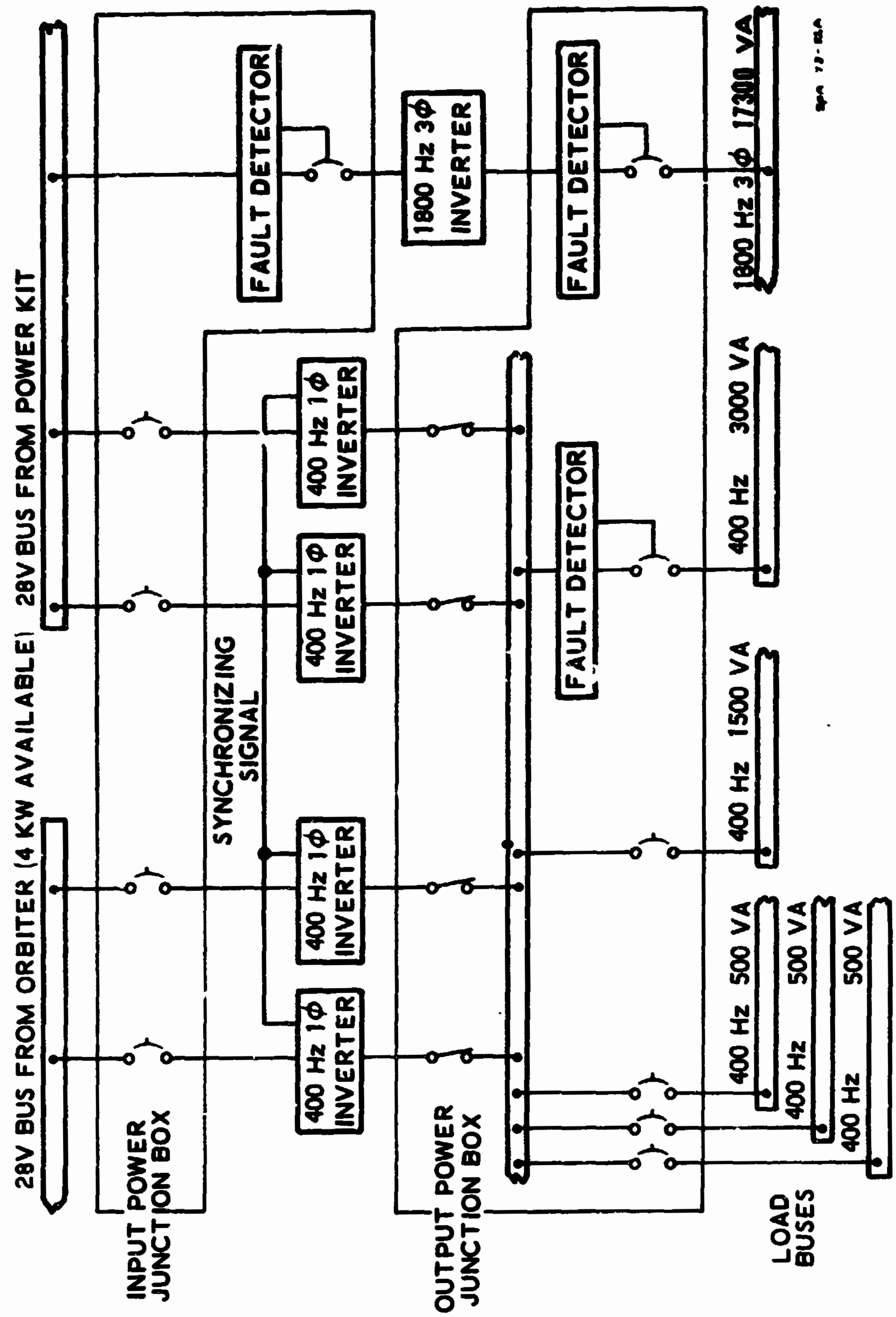


Figure 14. Spacelab Power Distribution

The output power junction box contains circuit breakers, switches and fault sensors for the load buses. The VA rating of the load buses should be kept as low as possible for protection purposes. A switch activated by fault detection circuitry is provided on the output of each inverter module so that a faulty module can be isolated from the bus.

Consideration should also be given to modularize both the input and output junction boxes into several separate modules so that in case of a major fault, some bus protection is provided by the physical separation of the switching elements. If all the circuit breakers and fault detectors were contained in a single enclosure, an overheating or fire could jeopardize the complete system.

3.5 THERMAL INTERFACE

Several thermal interfaces between the electrical power and thermal control subsystems were evaluated during the study. The primary interface is the dissipation of all electrical energy consumed by the experiments. That is, the energy under the experiment power source profiles presented in Section 3.1.3 must be dissipated by the thermal control subsystem. The dissipation of this energy requires additional electrical energy for operation of the thermal control equipment resulting in an increase in electrical energy that must be dissipated. Other thermal interfaces considered are the dissipation of heat from the fuel cells and the resultant by-product water produced by the fuel cells for potential use by the thermal control subsystem.

Based upon the experiment load requirements (Section 3.1) and assuming the use of the Power/Heat Rejection Kit (Section 3.3.2), a thermal control pump system electrical power requirement of 470 watts continuous was determined to satisfy the thermal control subsystem requirements. The approach assumes that any experiment equipment that receives power from the Spacelab uses the Spacelab thermal control capability. The 470 watts thermal control requirement is included in the experiment requirements and profiles that are presented in Sections 3.1.2 and 3.1.3.

If the Power/Heat Rejection Kit is not employed, the thermal control power requirements range from 300 to 600 watts continuous. For an air cooling thermal control approach, the requirements are 400 watts for air cooling fans plus an additional 200 watts for a water pump for the furnace

cooling. This results in a total thermal control requirement of about 600 watts continuous. The use of a liquid coolant loop will eliminate the fan requirement of 400 watts and replace it with a coolant loop pump requirement of approximately 100 watts. The 200 watt water pump for furnace cooling would bring the total continous power requirement to approximately 300 watts. For the experiments that do not require furnaces or inductance heaters, the thermal control requirements can be reduced by 200 watts.

Because a Power/Heat Rejection Kit is required to satisfy the experiment power requirements, the 470 watt continuous for the thermal control subsystem was assumed for all of the twelve representative experiments.

The Power/Heat Rejection Kit has a limited radiator area and additional cooling capability is required, therefore, the fuel cell byproduct water is made available for this purpose. The water production rate for each fuel cell in pounds per hour is presented in Figure 15 as a function of net power output of the fuel cells in kilowatts (reference 3). As noted, the water production rate for both the General Electric and Pratt and Whitney fuel cells are near the maximum rate presented. The water could be delivered to a water storage tank that contains a positive expulsion system that permits the water to be used for thermal control.

To assist in the definition of requirements and design of the thermal control subsystem in the Power/Heat Rejection Kit, the heat rejection and coolant exit temperatures for both the General Electric and the Pratt and Whitney fuel cells are presented in Figure 16 as a function of gross power output from the fuel cells. The individual fuel cells will operate between 2 kW and 12 kW each. For the case where both fuel cells are operating the minimum power will be 4 kW. The data presented in Figure 18 is dated information, however, it is the most recent manufacturer's data (Reference 5).

The heat rejection requirements for each of the fuel cell types is not significantly different. The differences in the coolant exit temperatures are considered to be primarily due to coolant flow rates. A fuelcell manufacturer has not presently been selected; however, for purposes of this study the worst case data are assumed relevant.

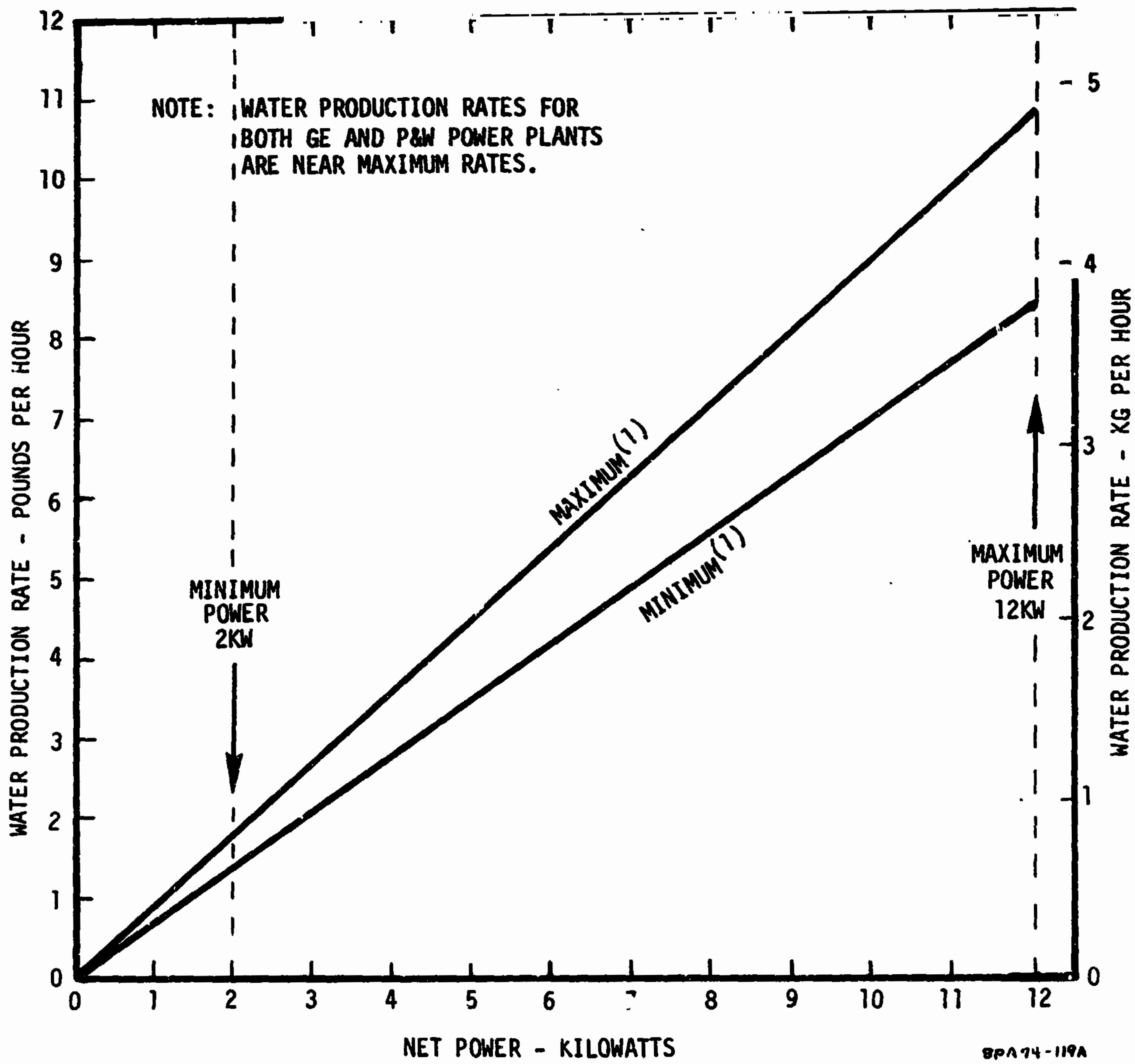


Figure 15. Fuel Cell Power Plant Water Generation Rate

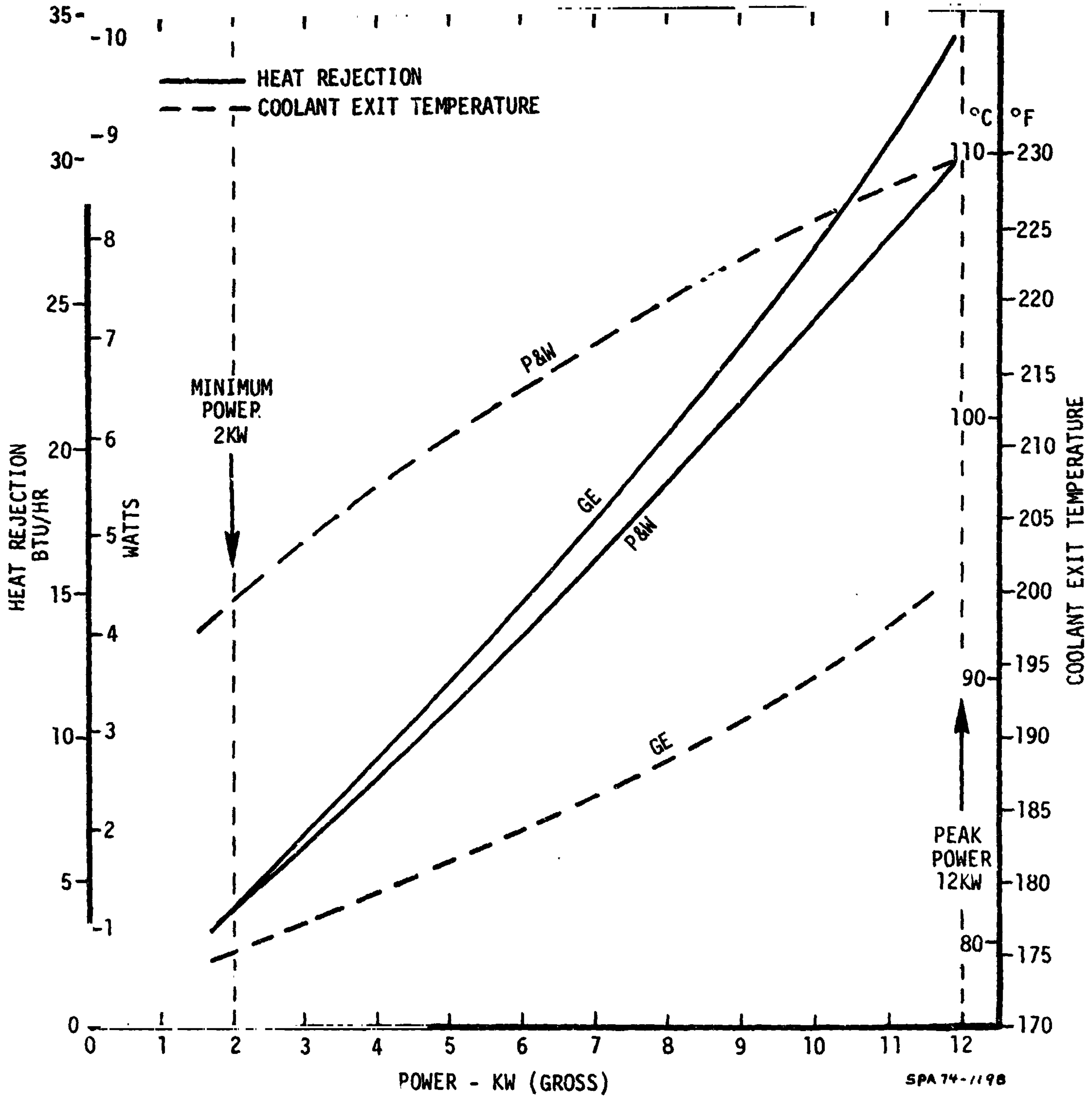


Figure 16. Fuel Cell Module Heat Rejection & Coolant Exit Temperature

4. THERMAL CONTROL SUBSYSTEM

The SPA thermal control subsystem (TCS) provides for thermal control of SPA equipment utilizing the heat rejection capability provided by the Spacelab. Although the Spacelab provides a one-atmosphere, shirt-sleeve environment, the absence of natural convection in the low gravity orbital environment requires that active thermal control be provided to SPA equipment*. The active thermal control can be provided by either supplying forced convection cooling, mounting equipment on liquid cooled racks, providing liquid coolant passages within the equipment, or providing combinations of all three. Since the SPA payloads consist of equipment which are of a commercial nature, thermal control can be accomplished with minimum change to equipment by providing cooling in the manner originally intended for the equipment except that forced convection cooling must be substituted for natural convection cooling. This means that electronics equipment will generally be air cooled and equipment (e.g. furnaces) that are cooled by facility water will be provided with a closed loop cooling system.

The SPA TCS must depend on the heat rejection provided by the Spacelab and/or an auxiliary heat rejection kit (see Volume II-D SPA Supplemental Power and Heat Rejection Kit). Since the Spacelab will provide approximately 4.2 kW cooling to payload equipment, a number of SPA payloads must depend on the auxiliary heat rejection kit to provide the necessary cooling. For those Spacelab payloads that do not require more than 4.2 kW electrical consumption at the power source the Spacelab provided cooling will be sufficient.

Several concepts for providing SPA equipment thermal control have been evaluated as to concept feasibility. Although detailed tradeoff studies were not conducted due to the preliminary nature of payload equipment and

*It is to be noted that experiments conducted during the Apollo 14 flight (Ref: LMSC Report HREC-5577-3, The Apollo 14 Heat Flow and Convection Demonstration Experiments, dated September 1971) led to the conclusion that there is significant natural convection energy transport present in a low-gravity field. However, a repeat of the experiments on the Apollo 17 flight did not exhibit natural convection behavior. A reassessment of Apollo 14 data confirmed the lack of significant natural convection in orbit (Ref: NASA TMX-64772, Apollo 17 Heat Flow and Convection Experiments, dated 16 July 1973).

Spacelab cooling resources definitions, sufficient analyses were conducted to identify SPA TCS and Spacelab interfaces, thermal control concept feasibility, thermal control concept limitations and areas of further investigation.

4.1 SYSTEM INTERFACES

The thermal control subsystem (TCS) interfaces are of two types depending on the subsystem being considered. In general the interfaces can be described as either physical or thermal. The physical interfaces are fairly straightforward and can be described in finite terms. The thermal interfaces are not as easily described since they depend on the interaction of the SPA TCS with the Spacelab TCS. A change in conditions on one side of the interface effects, and at the same time is affected by, conditions on the other side of the interface.

4.1.1 Physical Interfaces

The physical interfaces depend on the SPA TCS concept selected. The identified interfaces for the three concepts studies are summarized in Table 15. The requirement for a furnace water loop interface with the Spacelab water loop, while common to all three concepts, applies only for those SPA payloads flown without the auxiliary power kit containing either furnaces, certain of the heaters or the laser flash lamp.

The interfaces identified will be discussed more fully in the subsequent sections dealing with each TCS concept.

4.1.2 Thermal Interfaces With Spacelab

The thermal interfaces are generally common to all three concepts. The interfaces primarily are the temperature of the fluids entering the interface heat exchangers and the equipment waste heat rejected directly to the Spacelab cabin environment These interfaces are shown for specific payloads in the subsequent sections.

Effluents from the payload equipment will be considered in the Commercial Utility Assessment, however, the question of moisture addition or removal from the cabin atmosphere by the payload equipment has been reviewed. Moisture removal will occur when equipment is evacuated to a vacuum condition or cooled below the local dewpoint temperature. The

Table 15

PHYSICAL INTERFACES	
CONCEPT	INTERFACES
Air Cooling	1. Air ducting interface with Spacelab supplied payload equipment heat exchanger package. 2. Disconnects between furnace water loop heat exchanger and Spacelab water loop. 3. Structural mounts for fan cluster(s). 4 Structural support for air ducting.
Liquid Cooling	1. Fluid line disconnects with Spacelab supplied payload equipment heat exchanger package. 2. Disconnects between furnace water loop heat exchanger and Spacelab water loop. 3. Fluid line supports exterior to payload equipment racks.
Heat Pipe	1. Disconnects between furnace water loop heat exchanger and Spacelab water loop. 2. Air ducting interface with Spacelab supplied payload equipment heat exchanger package. 3. Structural mounts for fan package. 4. Structural support for air ducting. 5. Physical interface of heat pipes with electrical equipment.

amount of moisture removed will be a function of equipment use and cabin relative humidity.

Moisture removal will also occur as a result of condensation in areas where the surface temperature is below the dewpoint temperature. Such areas will be the interiors of refrigerated equipment and chilled lines within the confines of commercial equipment. The amount of moisture removed from the atmosphere as a result of access to the interior of the refrigerated equipment should not be significant, however, condensation on chilled lines and surfaces within the confines of commercial equipment could be. Generally speaking, these areas are insulated to some degree to minimize heat leak into the equipment. However, each item and payload will have to be reviewed to assess the moisture removal potential and the attendant impact, if any, on the Spacelab atmosphere moisture control system.

4.1.3 <u>Thermal Interfaces With Payload Equipment</u>

The thermal interfaces with the payload equipment are primarily the inlet temperatures of the coolants (air or water) required to provide the necessary waste heat removal rates at the design coolant flow rates. These temperatures are also dictated by the interaction of the SPA TCS with the Spacelab TCS. The interface requirements will vary from payload to payload, however, the subsequent sections dealing with each TCS concept will illustrate typical conditions to be encountered.

4.2 THERMAL CONTROL COOLING CONCEPTS

One of the key aspects of the SPA payloads is flexibility. The ability to combine different groups of experiments into a payload dictates that the supporting subsystems be flexible enough to accommodate a large number of combinations of input parameters. In the case of the TCS, this requires accommodating a wide range of waste heat rejections and equipment heat dissipation rates.

To assess the magnitude of the thermal control problem, three different thermal control system concepts were investigated to determine their capability to provide the necessary thermal control. While the assessment was of a preliminary nature, the concept analyses did indicate a number of areas where modifications to SPA timelines and/or equipment would be necessary.

A schematic diagram of a typical arch configuration equipment arrangement (immiscible solidification experiment) is shown in Figure 17. While this arrangement is not the only possible arrangement, it serves to illustrate the magnitude of the power dissipation in the rack-mounted equipment. Not shown in the figure is the waste heat from the furnaces which, as will be discussed later, are not included in the rack-cooling system. The power dissipations shown in Figure 17 are steady state power levels during the duration of an experiment cycle. While some of the equipment have transients (e.g. startup) which exhibit higher power dissipation levels, the thermal mass of the equipment absorbs most of this energy and the thermal control system does not react to these short-term transients.

4.2.1 Air-Cooling Concept

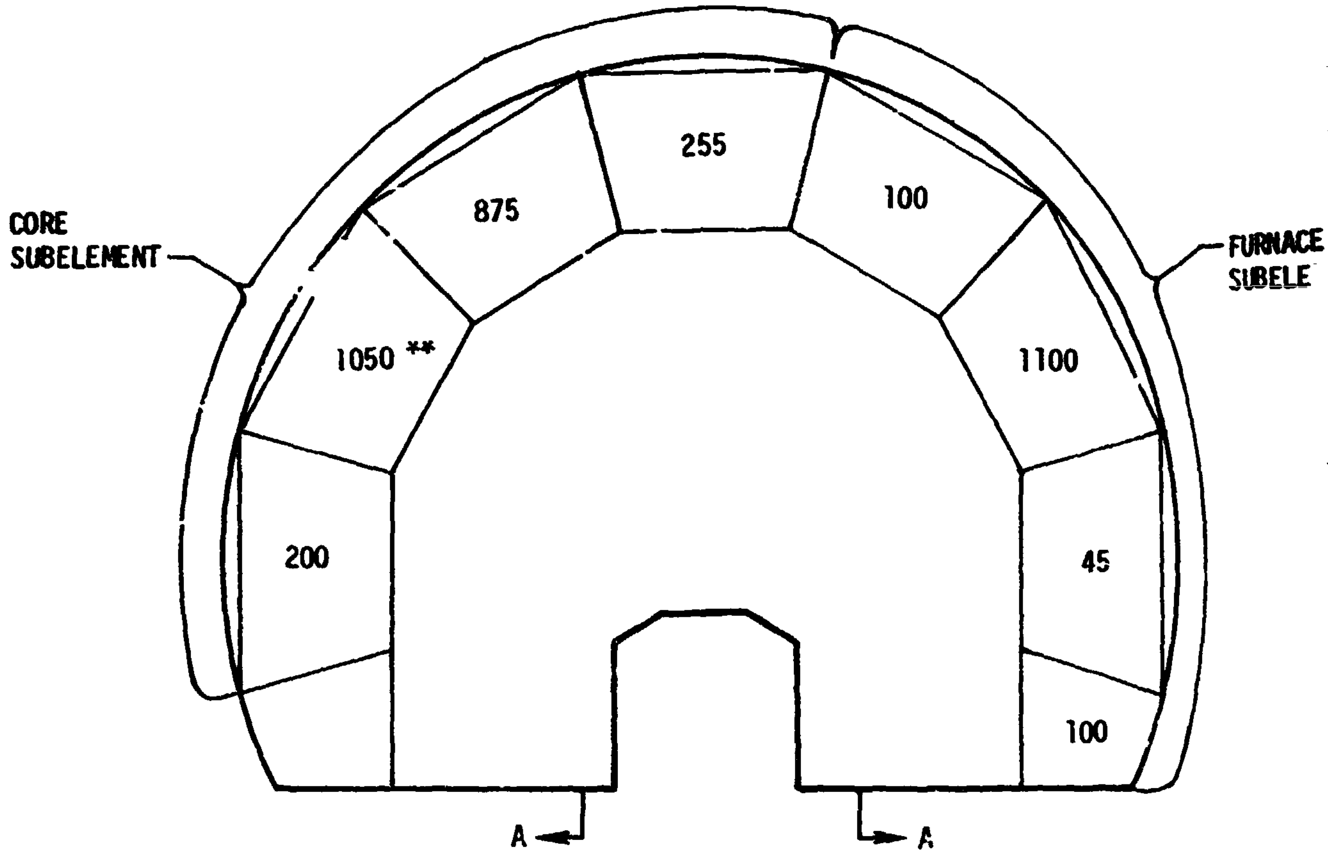
4.2.1.1 System Description

The air-cooling system concept is one that depends on the Spacelab supplied coolant flow for cooling of rack-mounted electronic equipment. The system schematic is shown in Figure 18. This schematic illustrates how the SPA system might integrate with the basic Spacelab thermal control system. The basic Spacelab coolant loop is the loop shown as 1-11 (i.e., inlet from either the Spacelab radiator or Shuttle interface heat exchanger is at point 1 and return is at point 11 in Figure 18). The SPA system air loop is shown as 10-12 and interfaces with the Spacelab coolant loop at the payload rack (PR) heat exchanger. It is anticipated that the PR heat exchanger would be supplied by the Spacelab and be permanently installed in the Spacelab coolant loop to minimize the number of disconnects and standardize the system for other Spacelab user payloads.

The air-cooling-loop distribution system will interface with the equipment racks with inlet and outlet supply headers as shown in Figure 19. The air distribution within each rack will be through the rack header. These headers will contain louvers which would be preset to provide the necessary rack airflow based on the heat dissipation in each rack.

The airflow will be provided by a fan cluster of 2 or 3 fans. Utilizing a fan cluster provides for system redundancy and could eliminate requirements for fan accessability for in-flight maintenance during the short-duration (7-day-long) missions. It is anticipated that the fan cluster

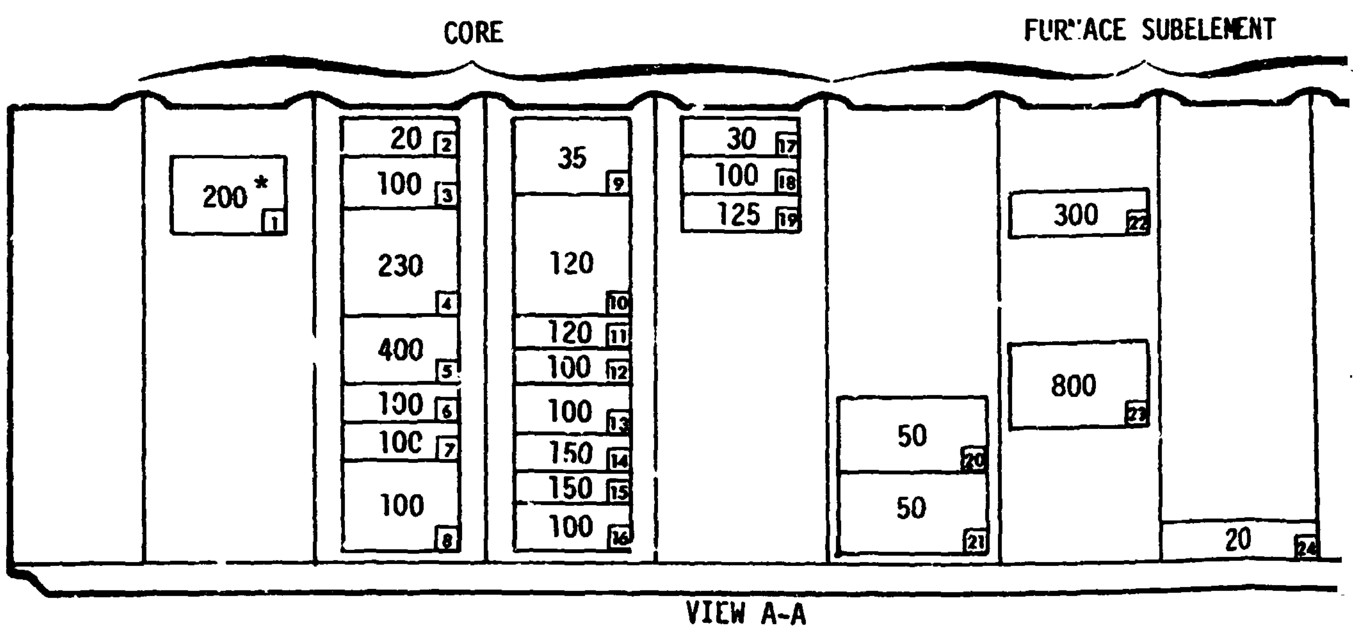
FOLDOUT FRAME 1



* Numbers indicate power dissipation in watts.

** Total power dissepation from rack in watts.

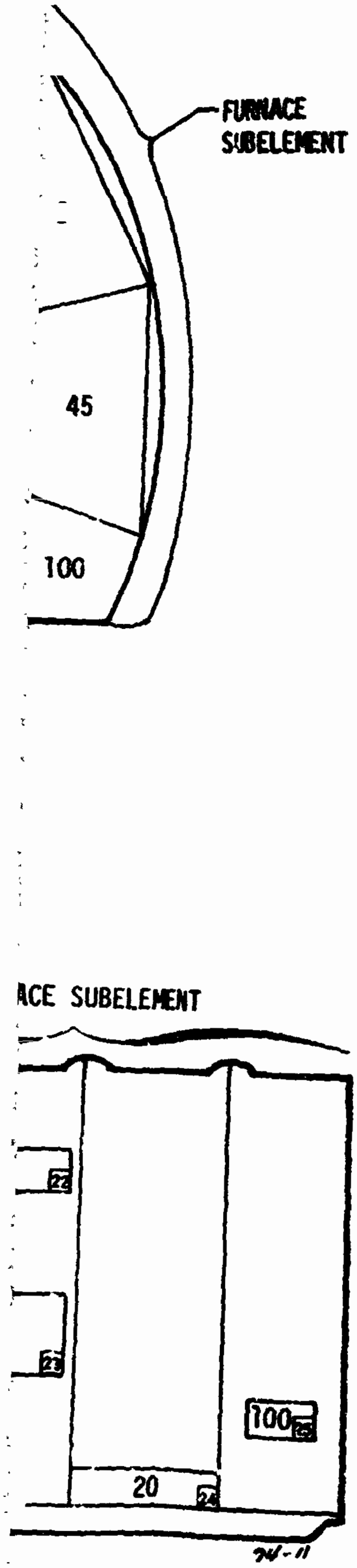
☐ Equipment item no.



VIEW A-A

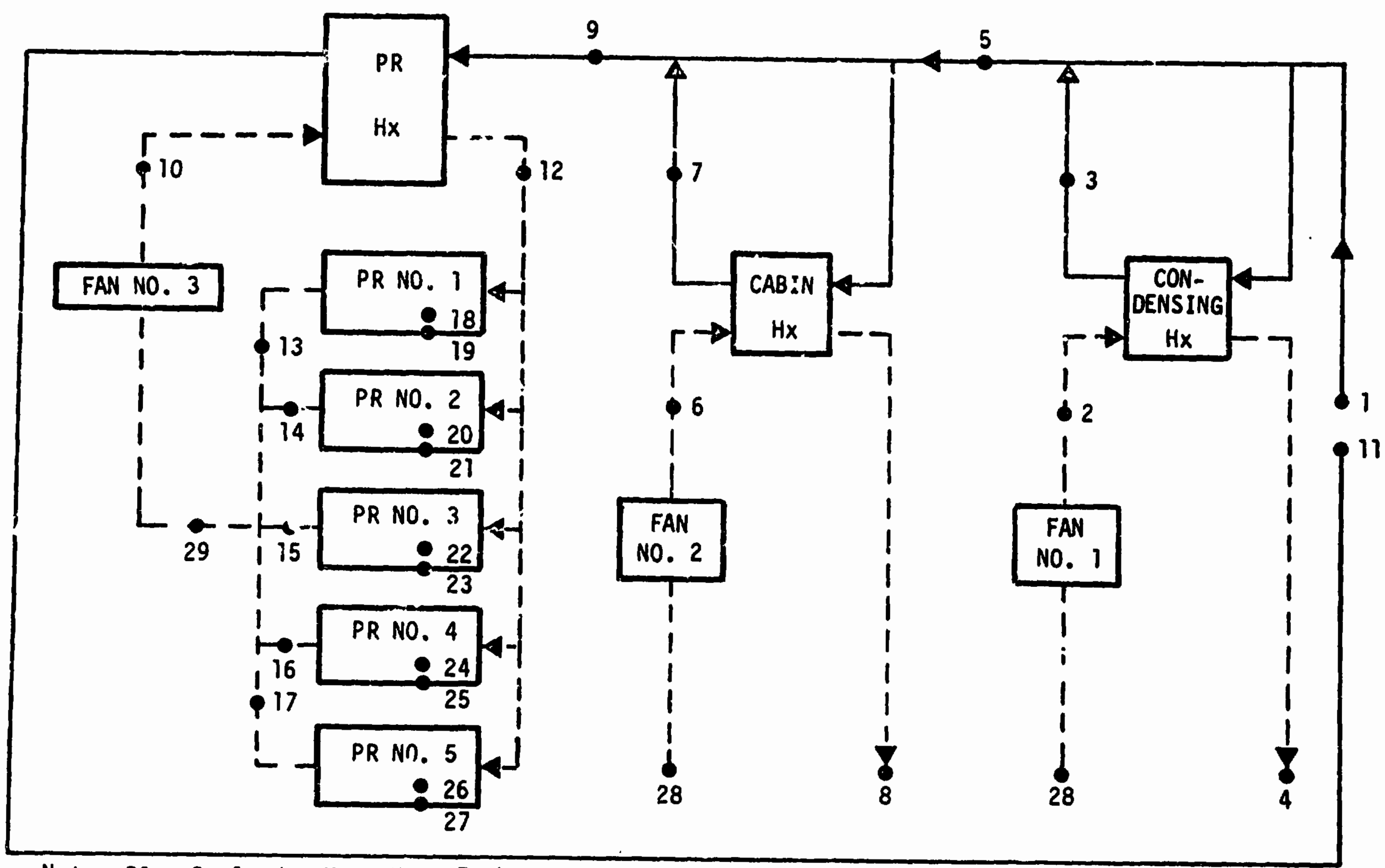
Figure 17. Equipm... Thermal Loads for Typical Immiscible Solidification Experiment.

FOLDOUT FRAME 2



ition Experiment.

ITEM NO.	PAYLOAD EQUIPMENT
1	Processor
2	Scanner Programmer
3	Oscilloscope
4	Operator Control Unit
5	Printer (Output)
6	Digital Volt Meter
7	Digital Clock
8	Analog (SCR) Controller
9	Signal Conditioner
10	Teleprinter
11	Tape Input
12	Multiplexer A/D Converter
13	Set Point Controller
14	Digital Storage Unit
15	Input/Output Stage
16	Storage Peripherals
17	Camera Control Unit
18	Slow Scan Sync.
19	Frame Storage Unit
20	Vacuum/Pressure Regulator
21	Vacuum/Pressure Measurement Unit
22	2-Color Pyrometer
23	Low Volt/High Amp Power Conditioner
24	Vacuum Pump Power Conditioner
25	High Vacuum Pump



Note: PR ≡ Payload; Hx ≡ Heat Exchanger

Figure 18. SPA/Spacelab Thermal Control System

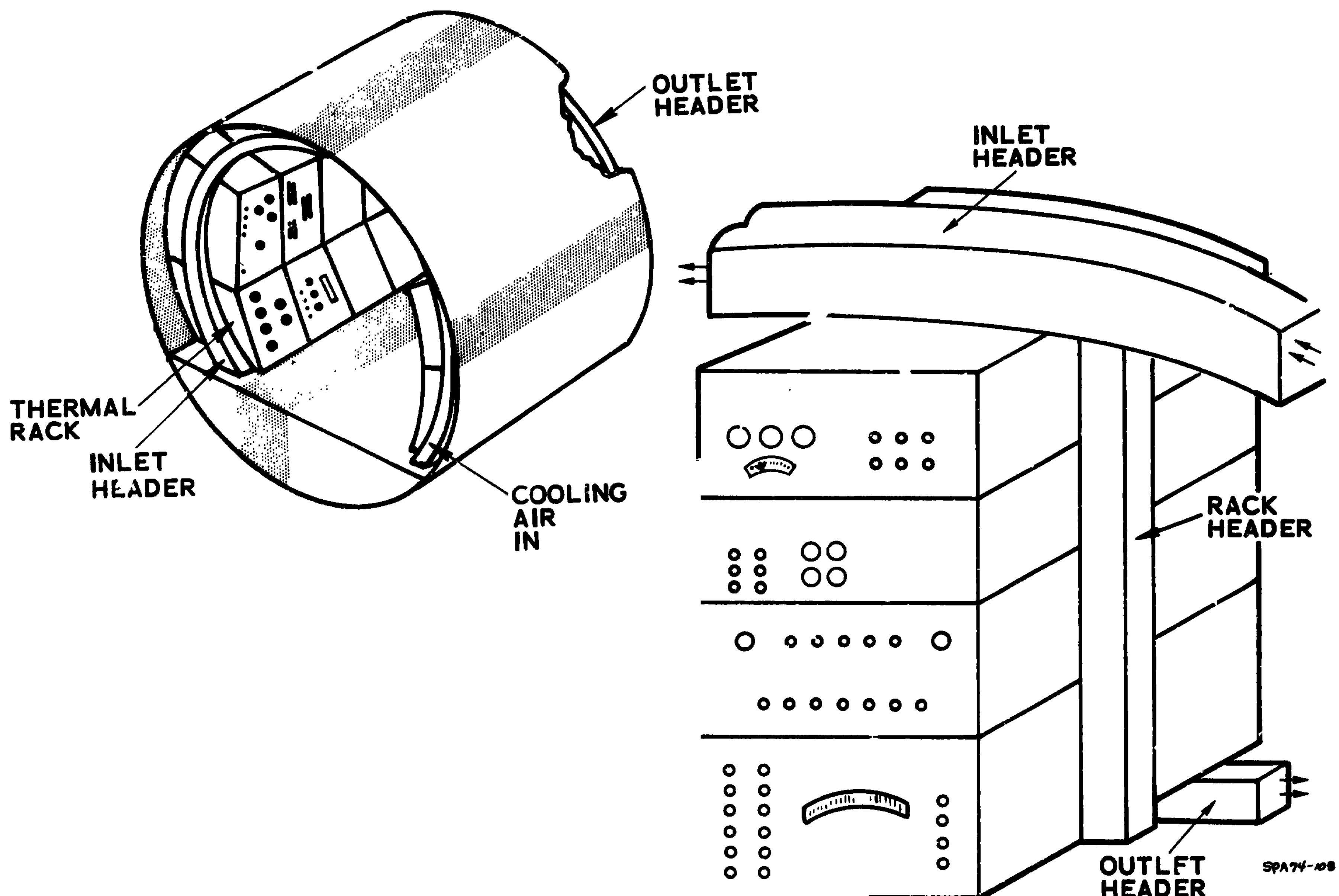


Figure 19. Rack Cooling Concept

power requirement will be on the order of 400 watts to deliver 20 m^3/min (700 cfm) at a head pressure of 5.5 - 3.5 kN/m^2 (0.5 - 0.8 psia).

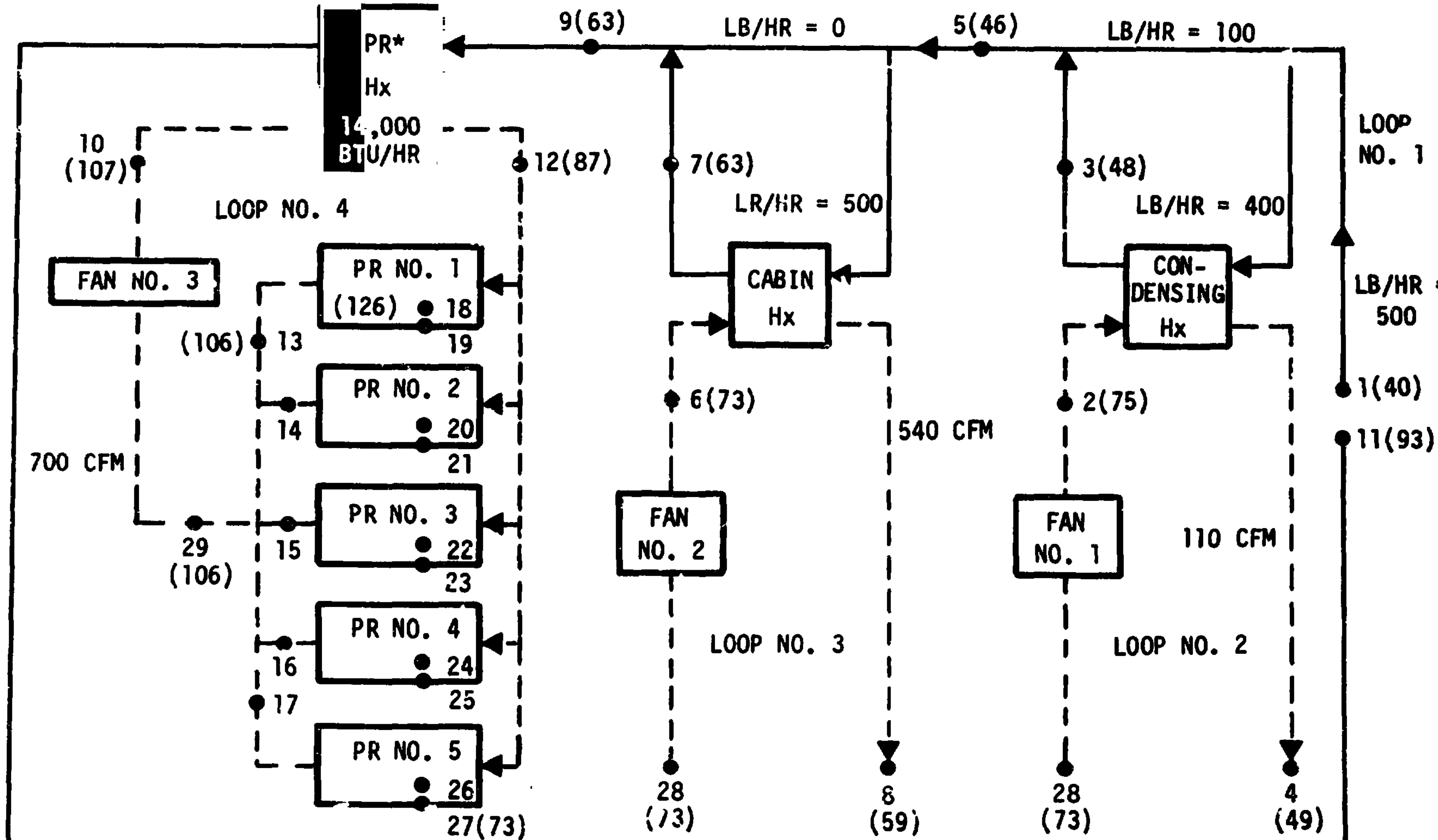
4.2.1.2 Analysis

An analysis was conducted to assess the performance of the air-cooling concept. Since the air-cooling concept interacts thermally with the Spacelab thermal control system, a simplified thermal model of a typical cabin thermal control system and the SPA air cooling loop was generated. The basis for the thermal model is the studies on the Sortie Lab conducted at the MSFC. The MSFC studies were used as a basis due to the lack of detailed definition of the Spacelab TCS during the analysis phase of the study.

Figure 20 shows the baseline Sortie Lab thermal control system and identifies nodal points of the analysis model constructed. Nodal point definitions are presented in Table 16. Loop No. 1 is the water loop which provides for heat rejection through a heat exchanger to an external heat rejection system (Shuttle radiators). It is assumed for this study that 230 kg/hr (500 lbs/hr) of water at a temperature of 4C (40 F) is provided. Loop No. 2 provides humidity control for the cabin while Loop No. 3 gives sensible heat removal from the cabin atmosphere. Loop No. 4 provides for heat removal from the experiments. The node point temperature predictions are shown in parenthesis for the idealized case where experiment components are perfectly insulated from the cabin atmosphere. Analyses were conducted with the thermal model and the results are shown in Figure 21 and 22.

Figure 21 shows results of analyses made of the air-cooling system using various values of rack-mounted equipment thermal conductance to the cabin and experiment power densities. As the component-to-cabin conductance (G1) increases, more heat is dumped into the cabin and the component bulk temperature decreases for a given power density. Although this helps in component cooling, the cabin temperature is increased as shown in Figure 24 and the rack panel surface temperature tends to increase.

The parameter P/C in the figures is the ratio of the component power to the heat transfer available from the component (effective thermal conductance). This parameter is used to compare different sizes of components on a common basis.



() ≡ Degrees Fahrenheidt
*Payload Rack

Figure 20. SPA Thermal Control System
(Thermal Model)

Table 16. SPA/Spacelab Thermal Control System
Thermal Model Nodal Points

NODE NO.	NODE DEFINITION	NODE NO.	NODE DEFINITION
1	Shuttle heat exchanger outlet	15	PR Outlet
2	Cond. Hx air side inlet	16	PR Outlet
3	Cond. Hx Liquid side outlet	17	PR Outlet
4	Cond. Hx air side outlet	18	PR#1 Interior (Aug)
5	Liquid loop downstream of Cond. Hx	19	PR#1 Surface
6	Cabin Hx air side inlet	20	PR#2 Interior (Aug)
7	Cabin Hx liquid side outlet	21	PR#2 Surface
8	Cabin Hx air side	22	PR#3 Interior (Aug)
9	PR Hx-S/L loop inlet	23	PR#3 Surface
10	PR Hx-SPA loop inlet	24	PR#4 Interior (Aug)
11	PR Hx-S/L loop outlet	25	PR#4 Surface
12	PR Hx-SPA loop outlet	26	PR#5 Interior (Aug)
13	PR Outlet	27	PR#5 Surface
14	PR Outlet		

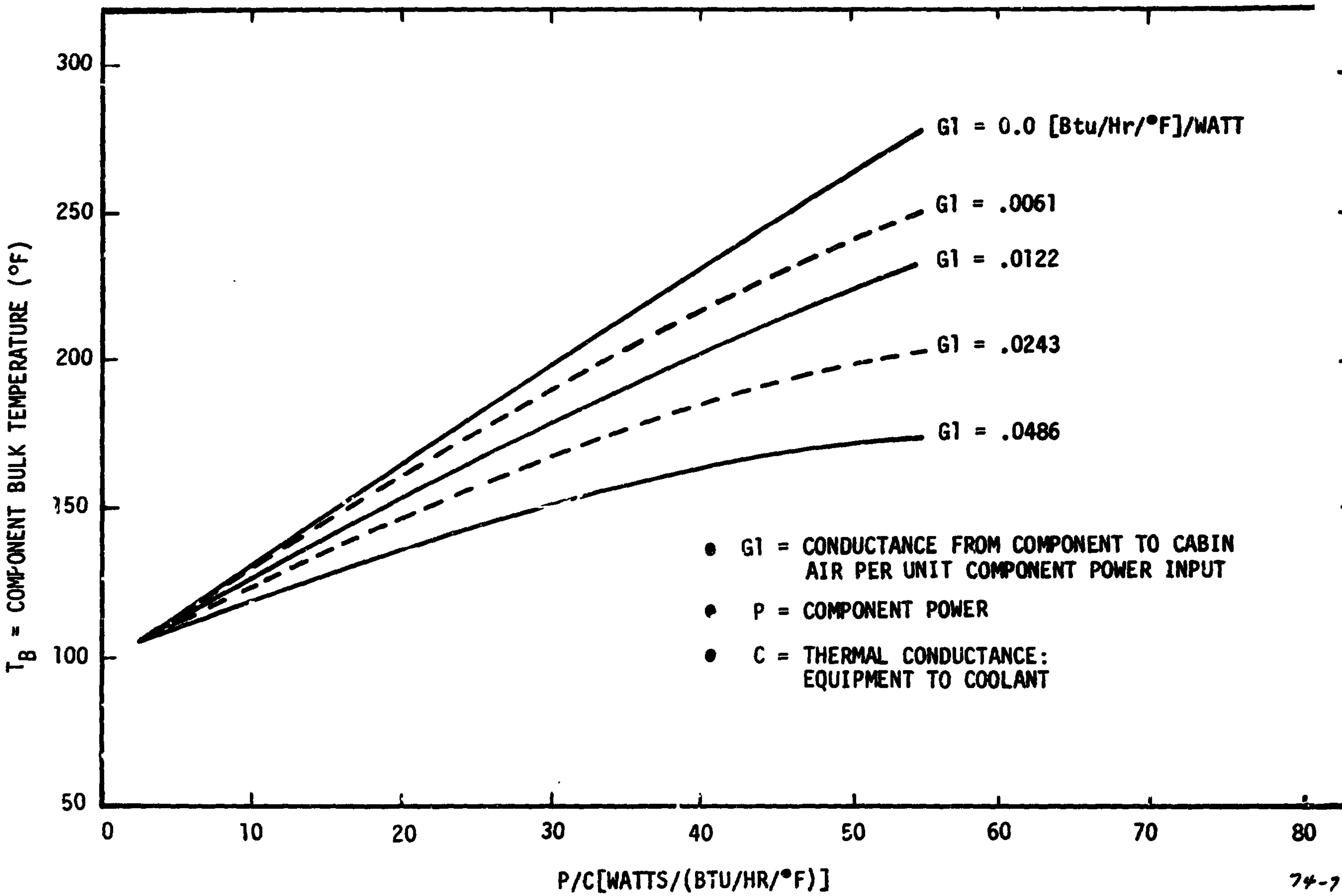


Figure 21. Experiment Component Temperatures

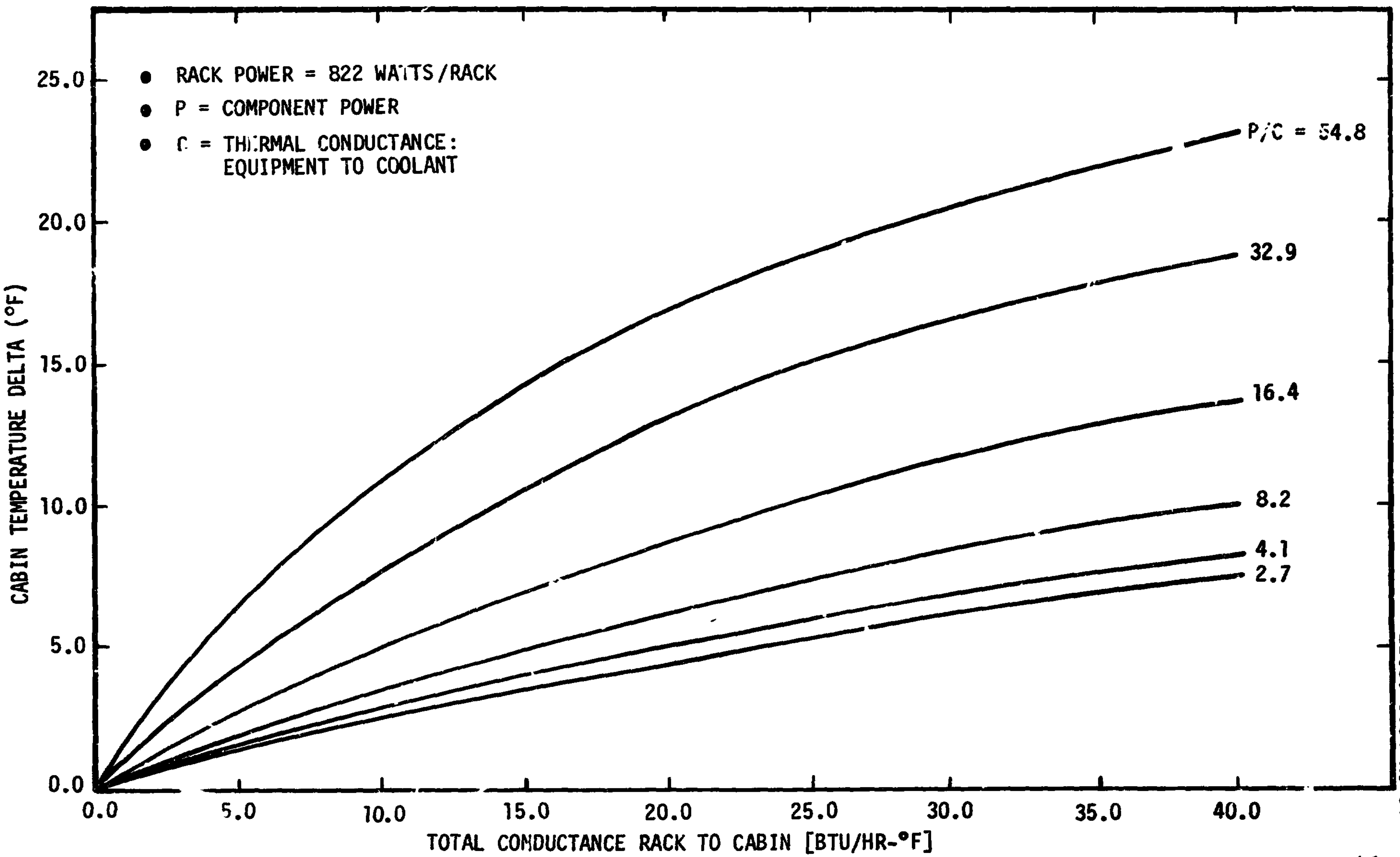


Figure 22. Effect of Experiments on Cabin Temperature

74-8

Since the SPA thermal control system interfaces with the Spacelab thermal control system all heat dissipated in the thermal racks ultimately effects the Spacelab cabin temperature. Because the thermal rack heat exchanger has limited capacity [approximately 4.1 kW (14,000 Btu/hr) power allocation], any increase in effective heat dissipation rate greater than the heat exchanger capacity ultimately affects the cabin temperature (either directly or by increasing system inlet temperature at Point 1 in Figure 20). Accordingly, there is a tradeoff between allowable cabin temperature rise, rack-mounted equipment bulk temperature and heat dissipation within the racks. This tradeoff is shown in Figure 23. This figure shows that if the cabin temperature is allowed to increase 3 C (5 F) as a result of SPA operation and the rack-mounted equipment is allowed to operate at approximately 60 C (140 F) the maximum heat dissipation per unit thermal conductance between the electronic equipment and the cooling air is 28 W·s·C/J (15 W·hr·F/Btu). For this condition the surface of the rack accessible to the crew would be in the 40 C (105 F) to 46 C (115 F) temperature range as a result of the temperature gradients between the component and cabin air.

4.2.1.3 <u>System Feasibility Assessment</u>

In order to assess the system feasibility it is nec[illegible]y to determine if the SPA payload rack-mounted equipment's pow[illegible]pation per unit thermal conductance to cooling air (P/UA) is with[illegible] al[illegible]able range shown in Figure 23. A survey was made of data availa[illegible] electronic equipment identified as SPA candidate equipment to [illegible]uip-ment thermal characteristics. A synopsis of the results of t[illegible]vey are shown in Table 17. As shown, all of the equipment surveyed fall within the required range except for the high voltage power conditioners and the mechanical mixing and dispersal unit. The waste heat from the conditioners was taken as 20 percent of the electrical input power to the conditioner. The high voltage conditioner needs to be more efficient and it requires a doubling of the heat transfer area to be within the allowable range.

The heat transfer characteristics of the air cooling system have been based on typical conditions, however, to assess the heat transfer characteristics and arrive at the required air flow, size of fans and fan power requires that an air flow test of a typical rack be performed.

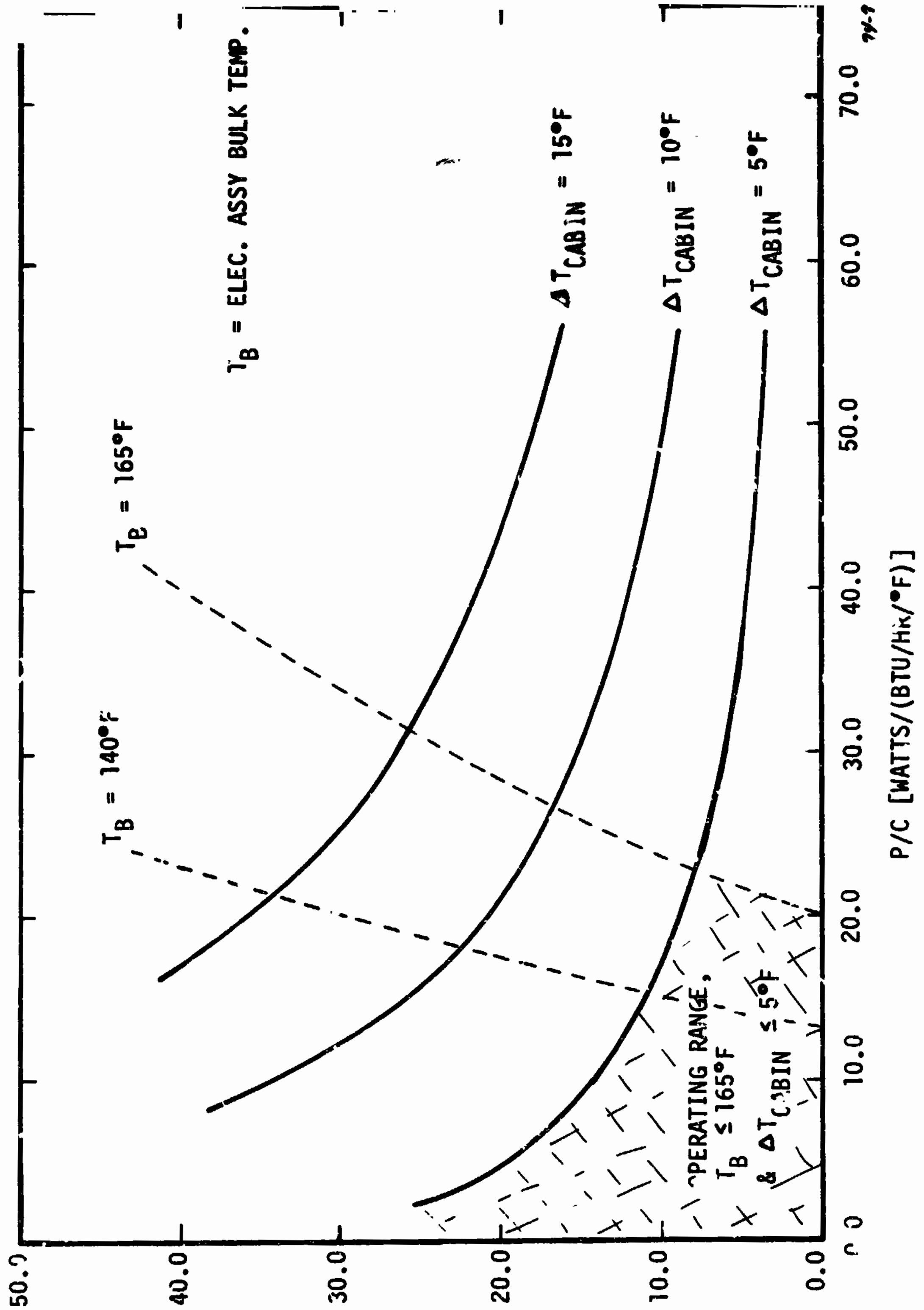


Figure 23. Experiment Thermal Control Requirements

Table 17. Summary of Typical Electronic Equipment Thermal Characteristics

COMPONENT	DIMENSIONS, m (ft) X	Y	Z	WASTE HEAT (WATTS)	P/A* W·s·C/J(W·hr·F/Btu)	WEIGHT kg(lb)	TIME CONST. s(HR)
Gas Chromatograph G16E	0.91 (2.98)	0.91 (2.98)	0.30 (0.98)	300	21.7 (1.27)	23 (50)	140 (0.04)
High Vacuum Pump F25E	0.30 (0.98)	0.30 (0.98)	0.46 (1.51)	50	17.4 (1.02)	23 (50)	650 (0.18)
Residual Gas Analyzer F12E	0.24 (0.79)	0.49 (1.61)	0.52 (1.71)	250	64.6 (3.78)	34 (75)	720 (0.20)
Vacuum/Pressure Meas. Unit F26E	0.24 (0.79)	0.49 (1.61)	0.54 (1.71)	50	13.0 (0.76)	6.8 (15)	140 (0.04)
Dialysis Unit B9E	0.30 (0.98)	[illegible] (0.98)	0.30 (0.98)	100	44.1 (2.58)	4.5 (10)	180 (0.05)
Gas Elimination System B13E	0.15 (0.49)	0.15 (0.49)	0.24 (0.79)	50	67.9 (3.97)	2.3 (5)	250 (0.07)
Lyophilization Unit B13E	0.76 (2.49)	0.55 (1.80)	0.37 (1.21)	200	24.1 (1.41)	91 (200)	900 (0.25)
Containerless Position Control Sys.	0.30 (0.98)	0.30 (0.98)	0.30 (0.98)	200	88.2 (5.15)	11 (25)	430 (0.12)
Digital Clock C1E	0.37 (1.21)	0.15 (0.49)	0.43 (1.41)	100	47.5 (2.78)	11 (25)	430 (0.12)
Multiplexer A/D Converter C14E	0.52 (1.71)	0.18 (0.59)	0.49 (1.61)	100	29.9 (1.75)	27 (60)	680 (0.19)
Printer (Output) C9E	0.37 (1.21)	0.30 (0.98)	0.43 (1.41)	400	125 (7.29)	23 (50)	580 (0.16)
Analog (SCR) Controller C13E	0.52 (1.71)	0.37 (1.21)	0.49 (1.61)	100	19.3 (1.13)	16 (35)	250 (0.07)
Digital Data Storage Unit C12E	0.52 (1.71)	0.30 (0.98)	0.49 (1.61)	150	33.3 (1.95)	18 (40)	320 (0.09)
Data Input/Output Stage C7E	0.52 (1.71)	0.15 (0.49)	0.49 (1.61)	150	49.2 (2.88)	18 (40)	500 (0.14)
Operator Control Unit C8E	0.52 (1.71)	0.52 (1.71)	0.49 (1.61)	230	34.7 (2.03)	27 (60)	360 (0.10)
Processor Unit C6E	0.52 (1.71)	0.34 (1.12)	0.49 (1.61)	200	41.0 (2.40)	27 (60)	470 (0.13)
Teleprinter C11E	0.52 (1.71)	0.76 (2.49)	0.34 (1.12)	120	15.6 (0.91)	23 (50)	250 (0.07)
Oscilloscope C18E	0.30 (0.98)	0.24 (0.79)	0.46 (1.51)	100	40.5 (2.37)	14 (30)	470 (0.13)
IR Spectrometer G8E	0.30 (0.98)	0.91 (2.98)	0.15 (0.49)	200	43.6 (2.55)	45 (100)	830 (0.23)
Laser Optical Scattering Monitor G6E	0.30 (0.98)	0.61 (2.00)	0.15 (0.49)	200	63.6 (3.72)	11 (25)	290 (0.08)
Low Volt/High Amp P/C B21E	0.30 (0.98)	0.46 (1.51)	0.46 (1.51)	800	204 (11.9)	41 (90)	860 (0.24)
High Voltage P/C B21E	0.30 (0.98)	0.30 (0.98)	0.30 (0.98)	1200	534 (31.2)	27 (60)	1000 (0.28)
RF Induction P/C F29E	0.30 (0.98)	0.30 (0.98)	0.30 (0.98)	200	89.1 (5.21)	16 (35)	580 (0.16)
Laser Pyrometer F9E	0.15 (0.49)	0.61 (2.00)	0.15 (0.49)	200	108 ([illegible])	11 (25)	500 (0.14)

*Based on a heat transfer coefficient of 56.8 J/(m^2·C·s) [10 Btu/(ft^2·F·hr)]

The number of fans and power requirements presented herein have been based on estimated pressure drops in the system and, as such, are approximations only.

Based on the analyses to date, it appears that air cooling is feasible providing the necessary P/UA can be provided on the commercial equipment. This could be accomplished by removing covers, adding fins and/or repackaging high power dissipation equipment. Analyses of individual equipment items with high P/UA values should be conducted to assure adequate cooling exists.

The air-cooling concept is recommended as the baseline system provided that the air flow tests verify adequate air distribution can be achieved. Equipment with high P/UA values may require modification in some manner.

4.2.2 Liquid-Cooling Concept

4.2.2.1 System Description

The liquid-cooling system is similar to the air-cooling concept except that the equipment mounting surfaces (cold plates) in the rack are cooled by coolant lines. The system schematic is identical to the air system schematic (Figure 18, Page 74) except the fan is replaced by a water pump and the PR heat exchanger becomes a water-heat exchanger. Figure 24 shows a concept of how the cold plates would integrate with the rack and electronic equipment.

The pump system is estimated to require approximately 100 watts for a water flow rate of up to 320 kg/hr (700 lb/hr). A pump package containing two pumps (one for redundancy) is recommended to alleviate any requirements for in-flight maintenance.

4.2.2.2 System Analysis

A parametric analysis was conducted to assess the feasibility of using a water cooling loop with cold-plate-mounted electronics. Figure 25 shows the electronics assembly bulk temperature as a function of water flow rate. The parameter P/C is the ratio of the electronics assembly waste heat (P) to the thermal conductance between the assembly and the coolant loop (C). As shown, the beneficial water flow rate is in the range

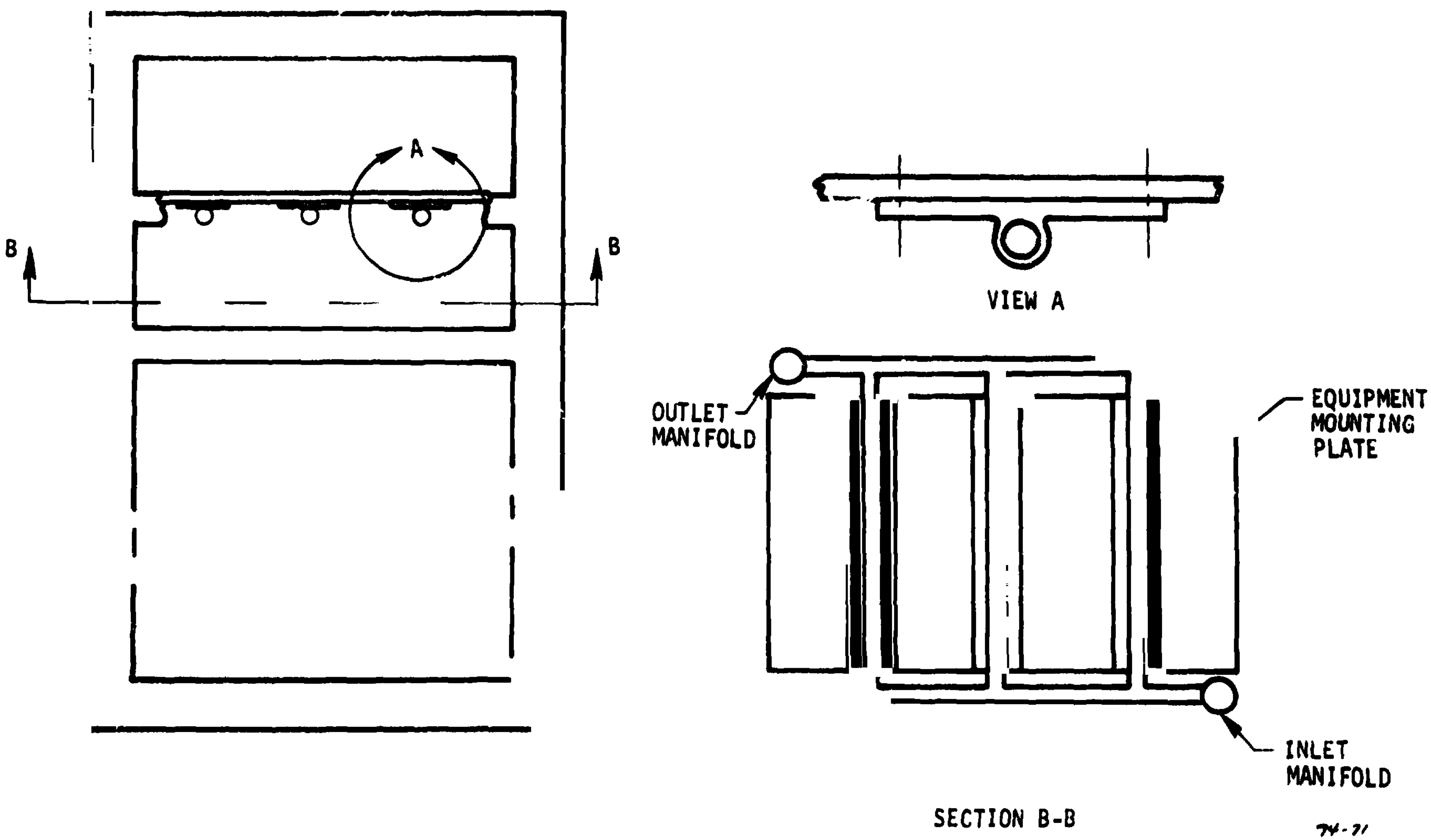


Figure 24. Liquid Loop Cold Plate

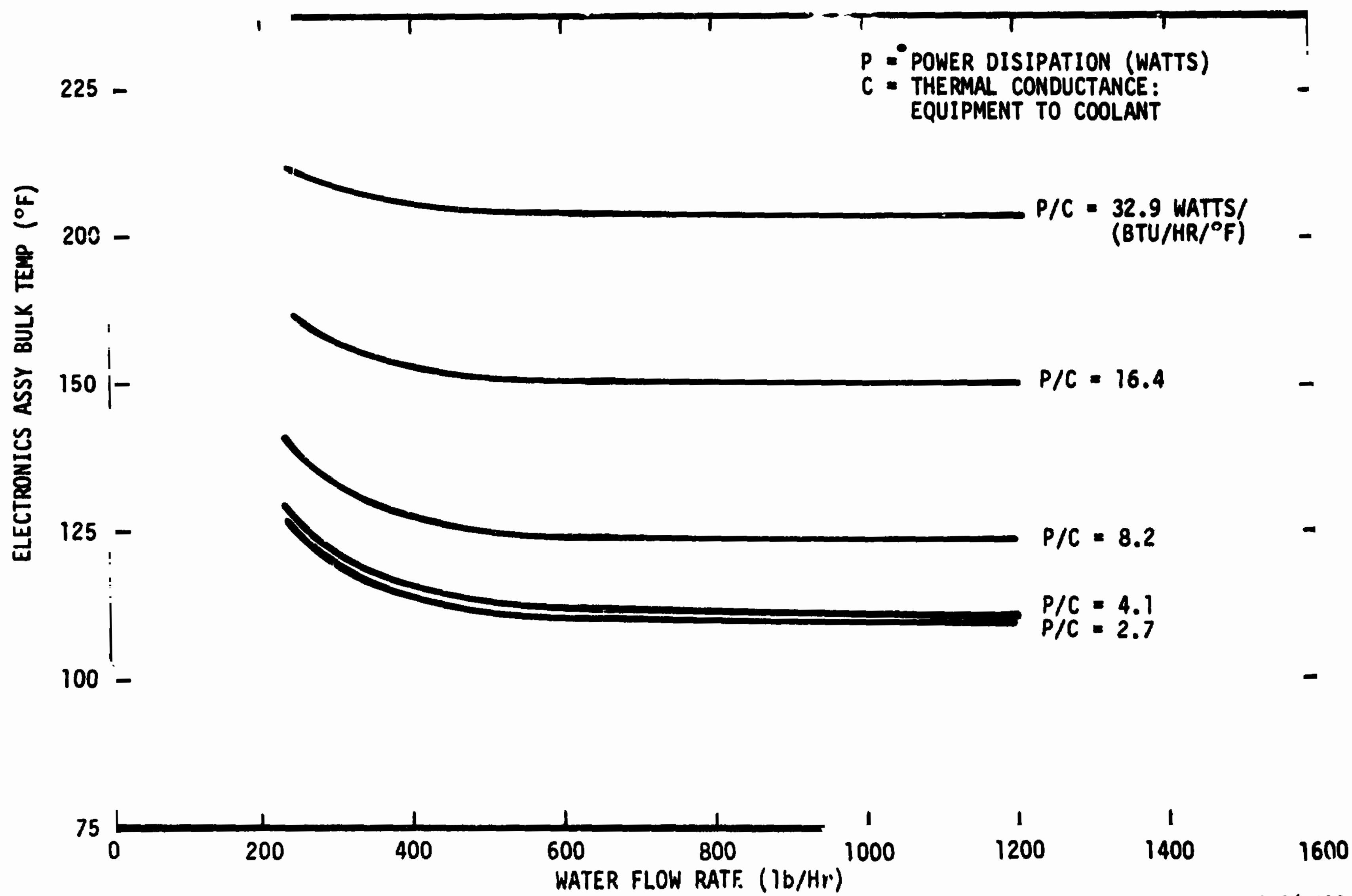


Figure 25. Liquid Cooling of Experiment Equipment

of 180-320 kg/hr (400-700 lb/hr). Since most of the electronic assemblies will have a P/C of less than 10, the water flow rate could be limited to approximately 180 kg/hr (400 lb/hr) with an attendant reduction in pump power.

The thermal coupling between the rack-mounted equipment and the cabin air is not too important in the coolant loop system when the equipment is mounted directly to the surface being cooled (cold plate). The thermal coupling should be established such that the equipment waste heat is dissipated directly to the coolant loop and dissipation to the cabin air is minimized. For a system water flow rate of 180 kg/hr (400 lb/hr), each rack (five racks in analysis) will have a flow rate of 36 kg/hr (80 lb/hr) if the flow splits are equal. Assuming a cold plate efficiency of between 80 and 90 percent, a total heat dissipation of 1.5 kW can be handled in any rack based on a coolant inlet of 7 C (45 F) and an average P/C of approximately eight.

4.2.2.3 System Feasibility Assessment

The liquid-cooling concept feasibility depends to a large extent on the design of the liquid distribution system. That is, the system must provide the required flow rate at a low enough pressure drop to result in a reasonable pump power requirement. In addition, the thermal loads on each portion of the loop (equipment racks) must be balanced sufficiently so as to maintain rack outlet temperatures below the vapor generation temperature at local line pressure. The thermal load on any component plate should be limited, based on pressure drop, to maintain adequate outlet temperature in the fluid.

To completely assess the coolant loop characteristics, detailed thermal analyses are required on a specific configuration. Based on the preliminary analyses to date a liquid cooling loop would appear to be feasible.

4.2.3 Heat-Pipe Concept

4.2.3.1 System Description

A heat-pipe system was investigated since such a system provides the capability of thermal energy transport without an attendant expenditure of power for an electromotive device (fans, pumps, etc.). However, the heat

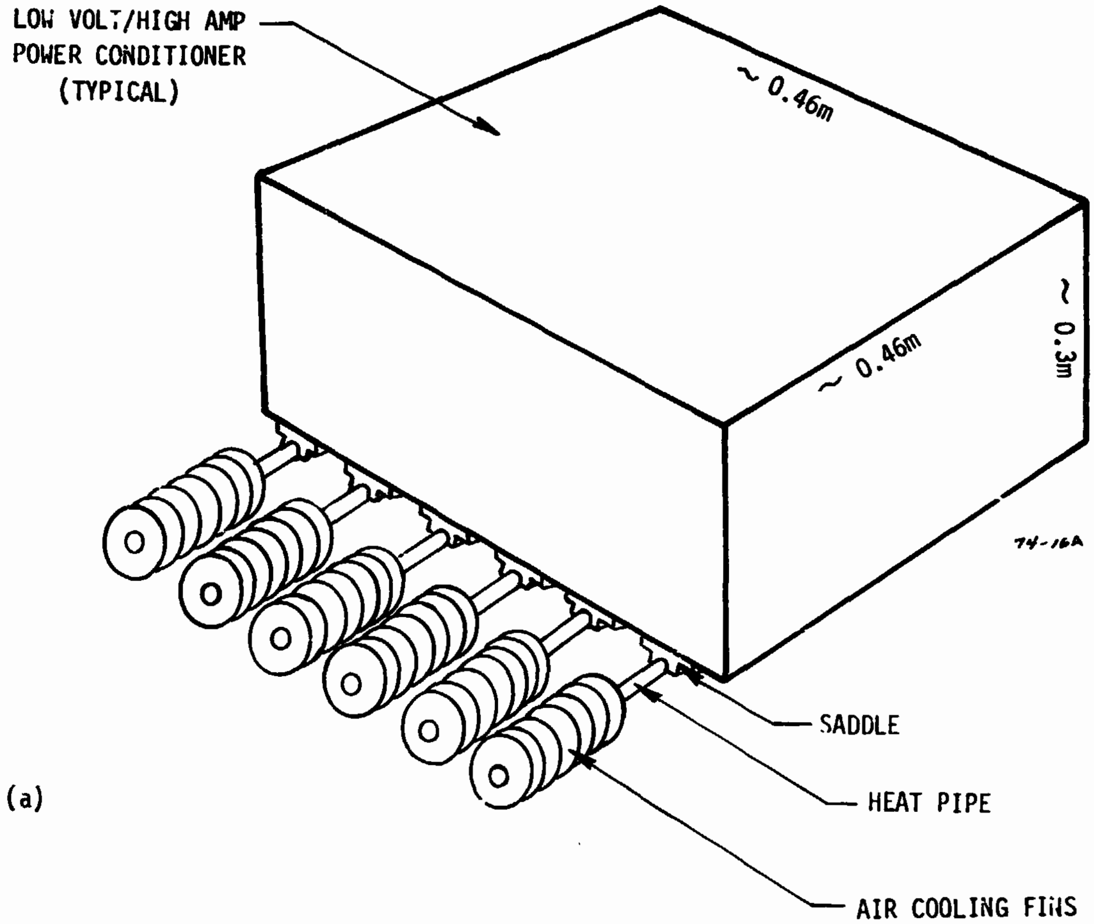
transport requirements on the heat-pipe system resulting from a typical rack power dissipation distribution (Reference Figure 17) are too severe. For example, a heat pipe capacity of nearly 760,000 W-cm (300,000 Watt-in.), which is the thermal energy times distance it must be transported, is required to transport the core equipment heat dissipation. While this requirement could be satisfied by a multiple pipe system, the number of pipes required is considered impractical in relation to air or pumped liquid cooling.

Heat pipes can transport high heat loads for short distances very efficiently, thus, it seems more reasonable and practical to provide air ducts from the ECS system to ducts behind the equipment racks. Heat pipes can be used as illustrated in Figure 26 for dumping their heat from the various components into the duct. The heat pipes are attached to the components and therefore are installed with a minimum effort.

The first concept illustrated in Figure 26 utilizes heat pipes attached to the component and extending into an air duct. The heat is dissipated to the air via the air cooling fins attached to the heat pipes. The number of heat pipes required on each piece of equipment is a function of the power dissipation (the low voltage/high amp power conditioner would require six as illustrated in the figure). The second concept illustrates the use of a panel heat pipe to distribute discrete heat loads uniformly to air cooling fins. The air flow would be ducted along the cooling fins from an inlet header to an outlet header.

4.2 3.2 System Analysis

In order to select heat pipes for the various SPA equipment cooling requirements, the performance in terms of watt-inches has been mapped out for various wick structures and working fluids over the anticipated temperature range. The performance maps are shown in Figures 27, 28 and 29 for round arteries, homogeneous wick and square or rectangular axial-grooves, respectively. Water, ammonia and methanol are the candidate working fluids over the temperature range from 32 C (90 F) to 66 C (150 F). These curves serve as a guide for preliminary selection and sizing of the wick for a given requirement. They show what heat pipes can and cannot do, but should not be used for estimating performance of a particular heat pipe. The curves are valid only for zero-gravity and negligible



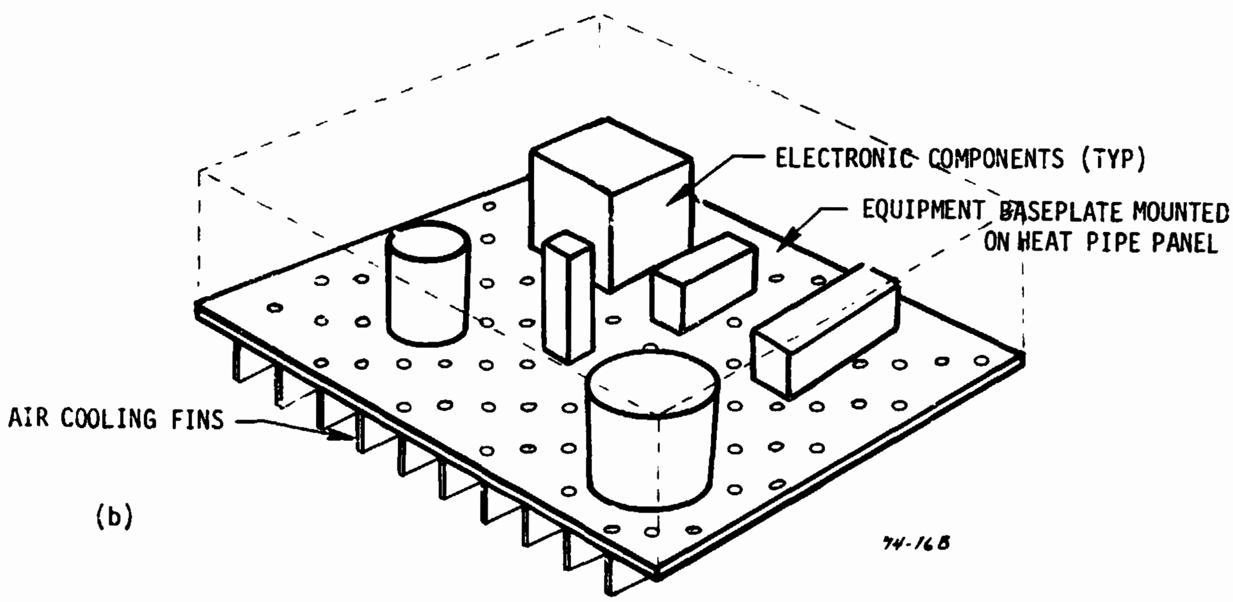


Figure 26. Heat Pipe Cooling Concept for Rack Mounted Equipment

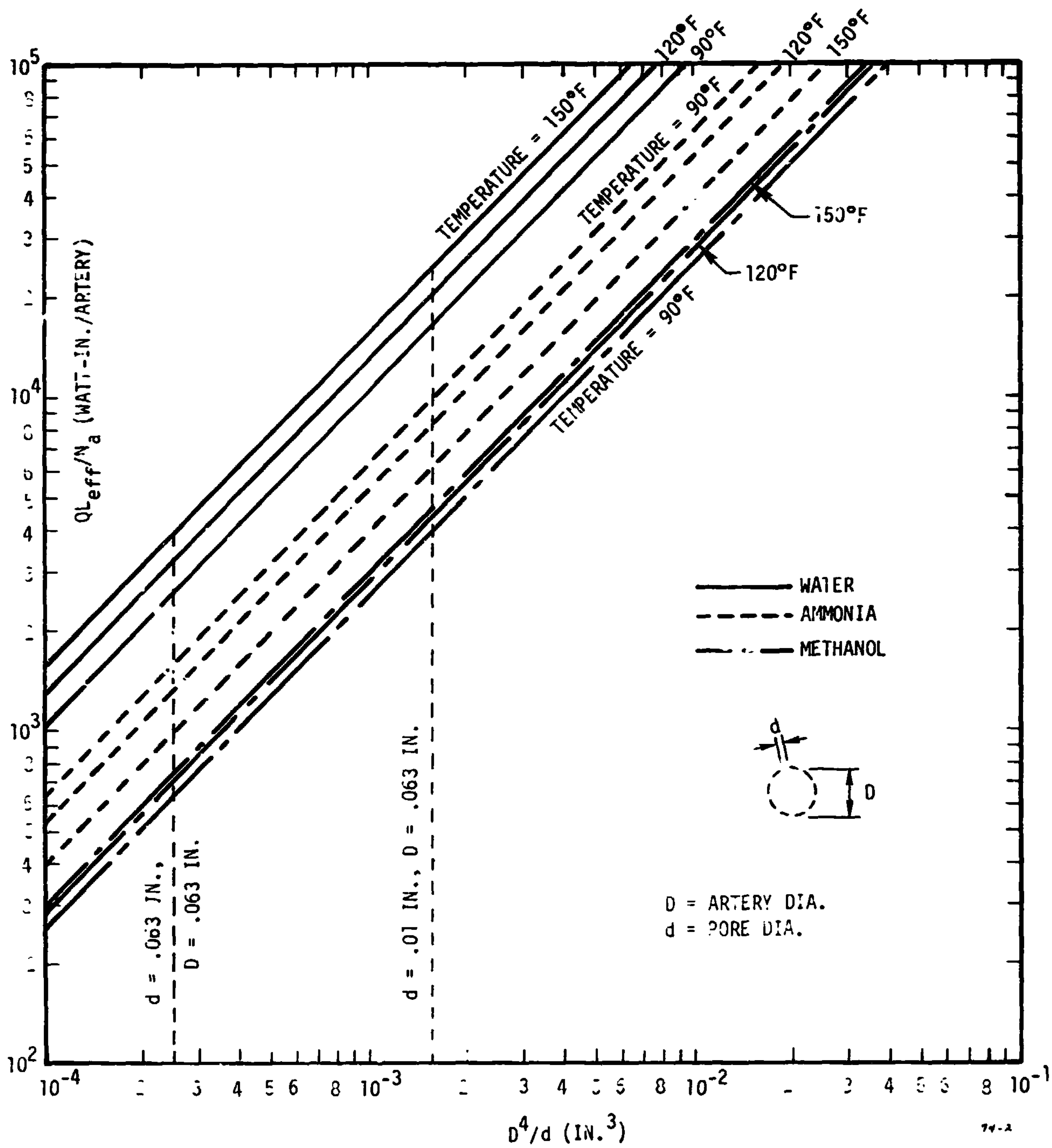


Figure 27. Zero-Gravity Artery Performance with Negligible Vapor Loss

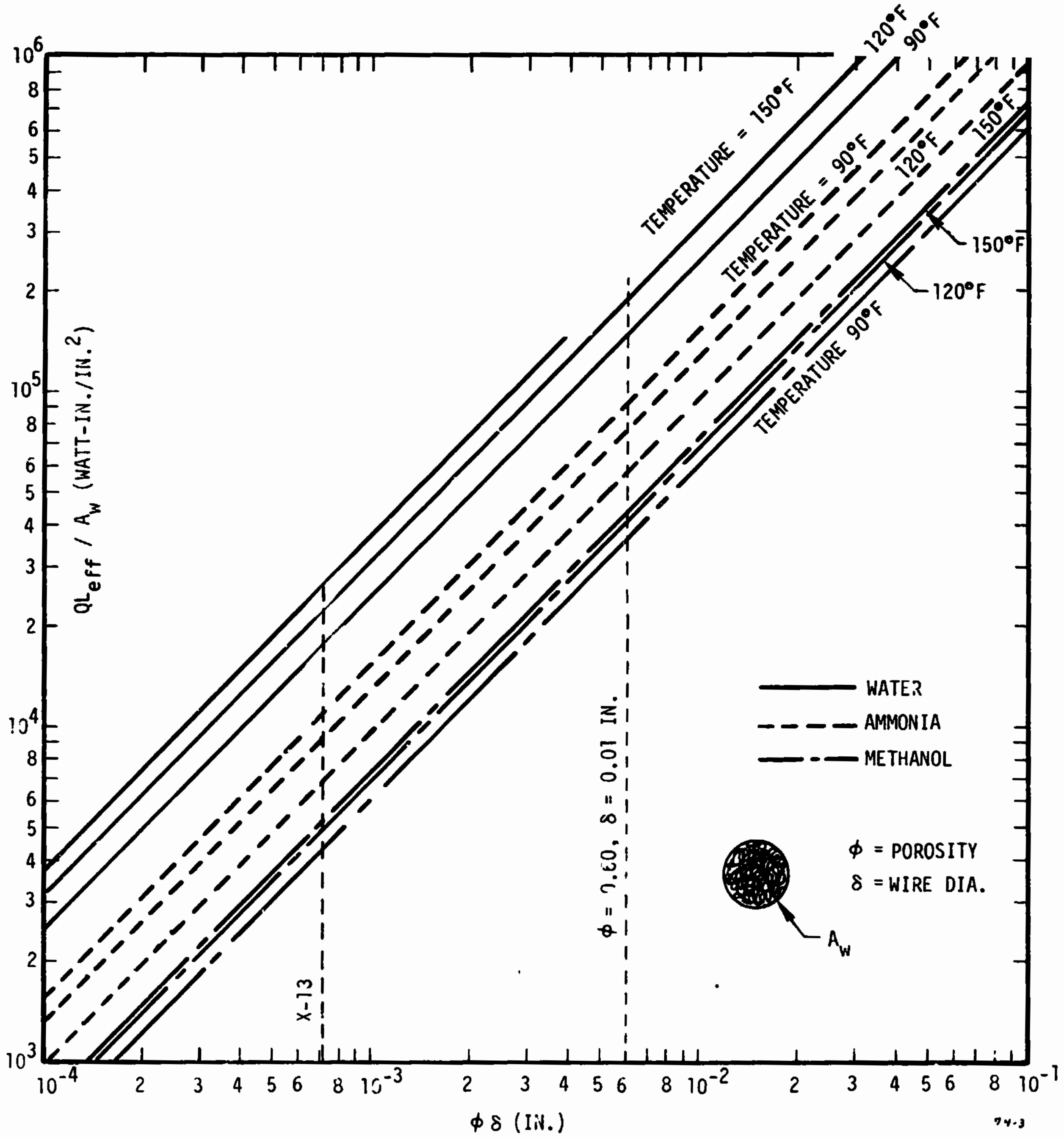


Figure 28. Zero-Gravity Wick Performance with Negligible Vapor Loss

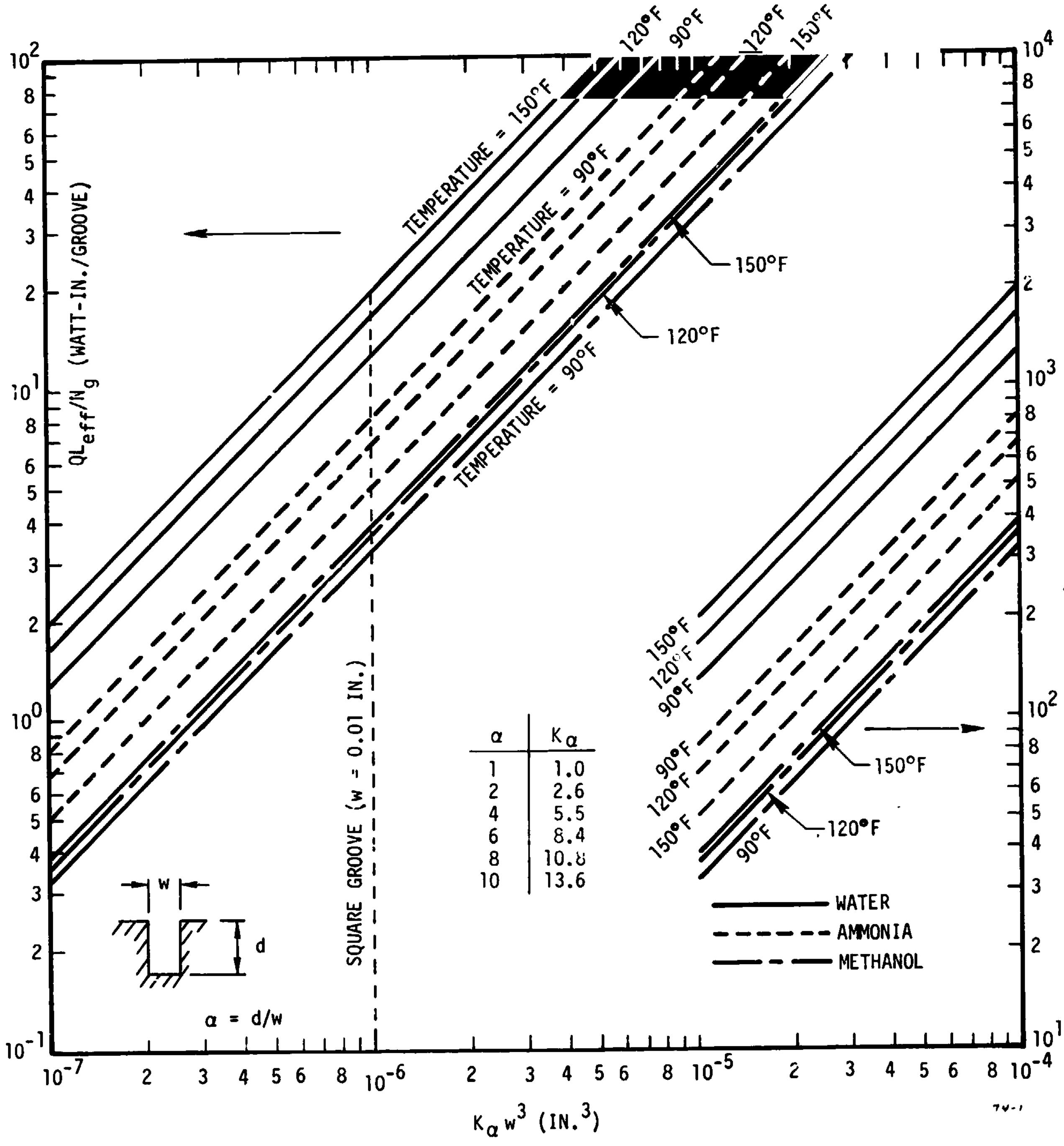


Figure 29. Zero-Gravity Axial Groove Performance with Negligible Vapor Loss

vapor loss. The effect of fillets, meniscus recession, etc., have been neglected and one should refer to the TRW MULTIWICK computer program for estimating heat pipe performance [Reference 8].

A few examples of typical wick dimensions are shown on the curves as dashed lines. The heat transport capability (QL_{eff}) is defined as follows:

$$QL_{eff} = \sum_{i=1}^{n} \bar{Q}_i L_i$$

where $\bar{Q}_i$ is the average rate of heat transport through a given section of the pipe and L_i is the length of the section. Another way of defining $\bar{Q}_i$ is the sum of all heat input up to the given section plus the average of the incremental heat input or rejection in the length, L_i. Uniform heat input and output are implied over each length.

4.2.3.2.1 <u>External Heat Transfer</u>

The rate of heat transfer through the heat pipe is governed by the amount of heat that can be dumped to the cooling air. For a given amount of external condenser area and air flow rate, the heat rejection is limited by the temperature difference between the heat pipe (T_{hp}) and the cooling air (T_a). That is,

$$Q = \eta h A' L_c (T_{hp} - T_a) \tag{1}$$

The fin efficiency, η, and the heat transfer coefficient, h, are functions of the air velocity. A' represents the total heat transfer area per unit length of condenser. The grouping $\eta hA'$ is plotted as a function of air velocity for various fin configurations in Figures 30, 31 and 32. These curves are useful for sizing heat pipes of the type shown in Figure 28. Similar results could be generated for other cooling methods.

4.2.3.2.2 <u>Design Approach</u>

The heat-pipe-system concept can be separated into the selection of the heat-pipe design and the design of the overall system including air-duct configuration, fan(s) selection, etc. Since the design of the air-duct system and overall system performance analysis would be similar to the air-cooling concept discussed in Section 4.2.1 with the heat pipe

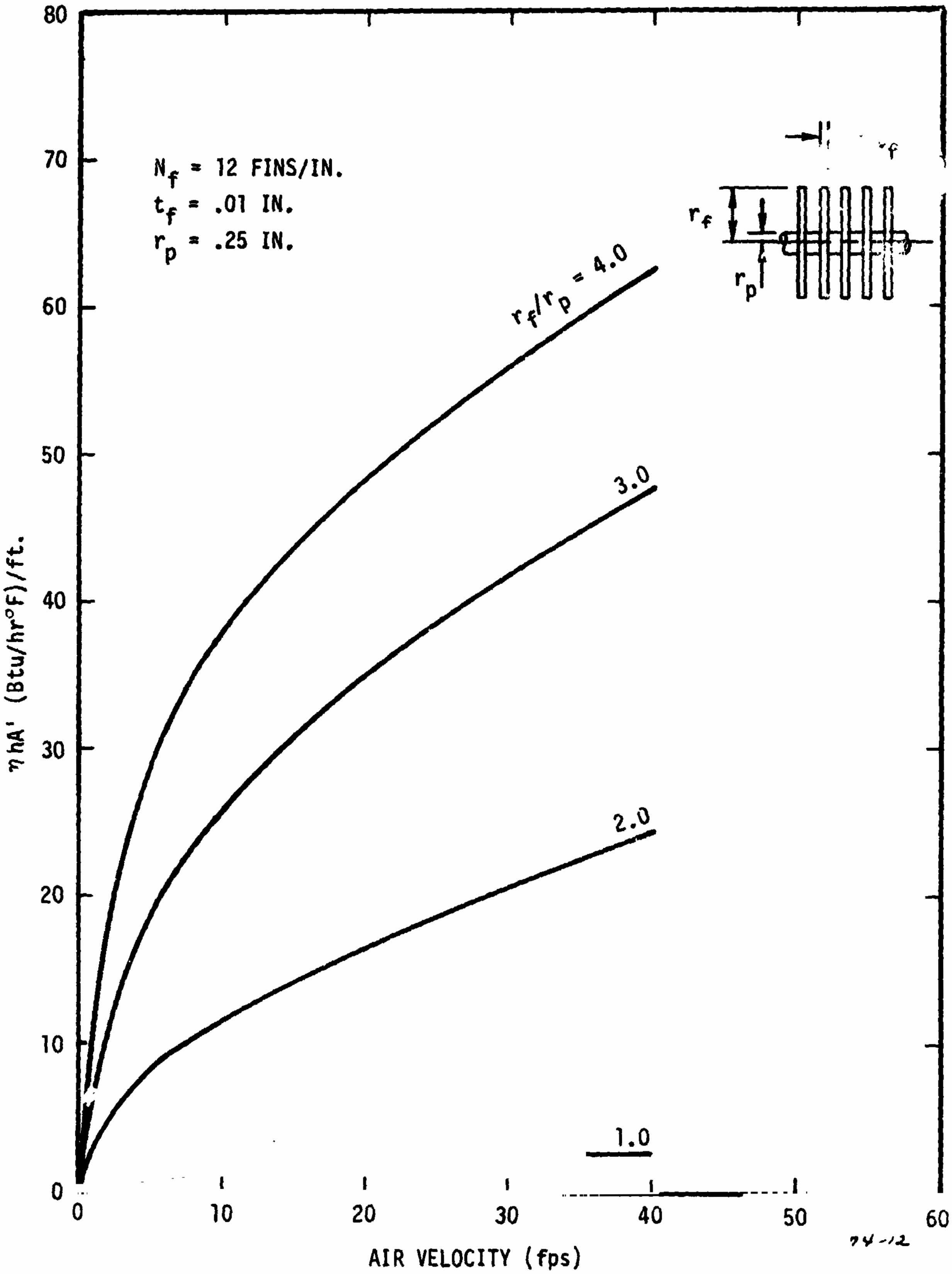


Figure 30. Air-Side Conductance for Finned Tubes

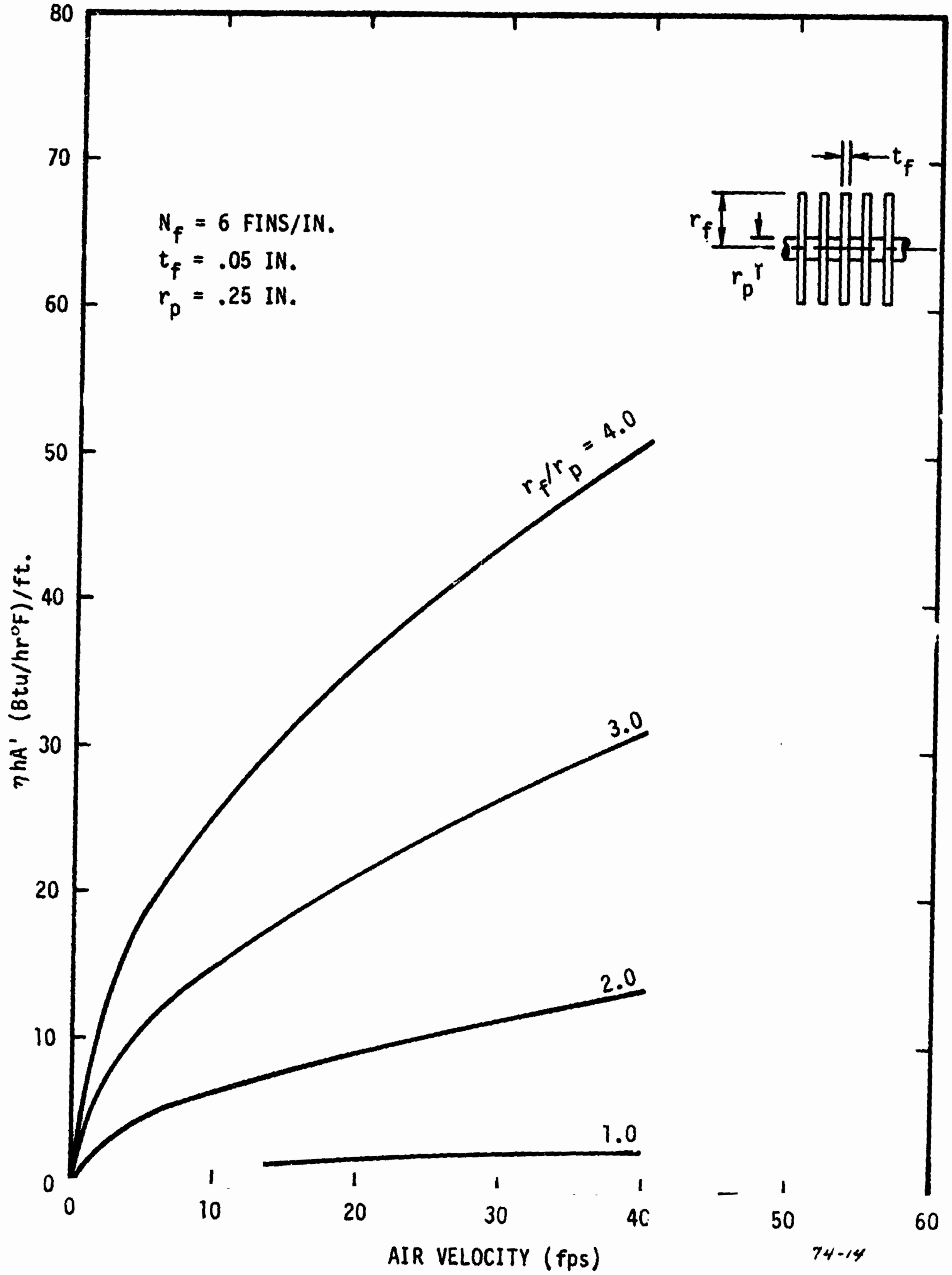


Figure 31. Air-Side Conductance for Finned Tubes

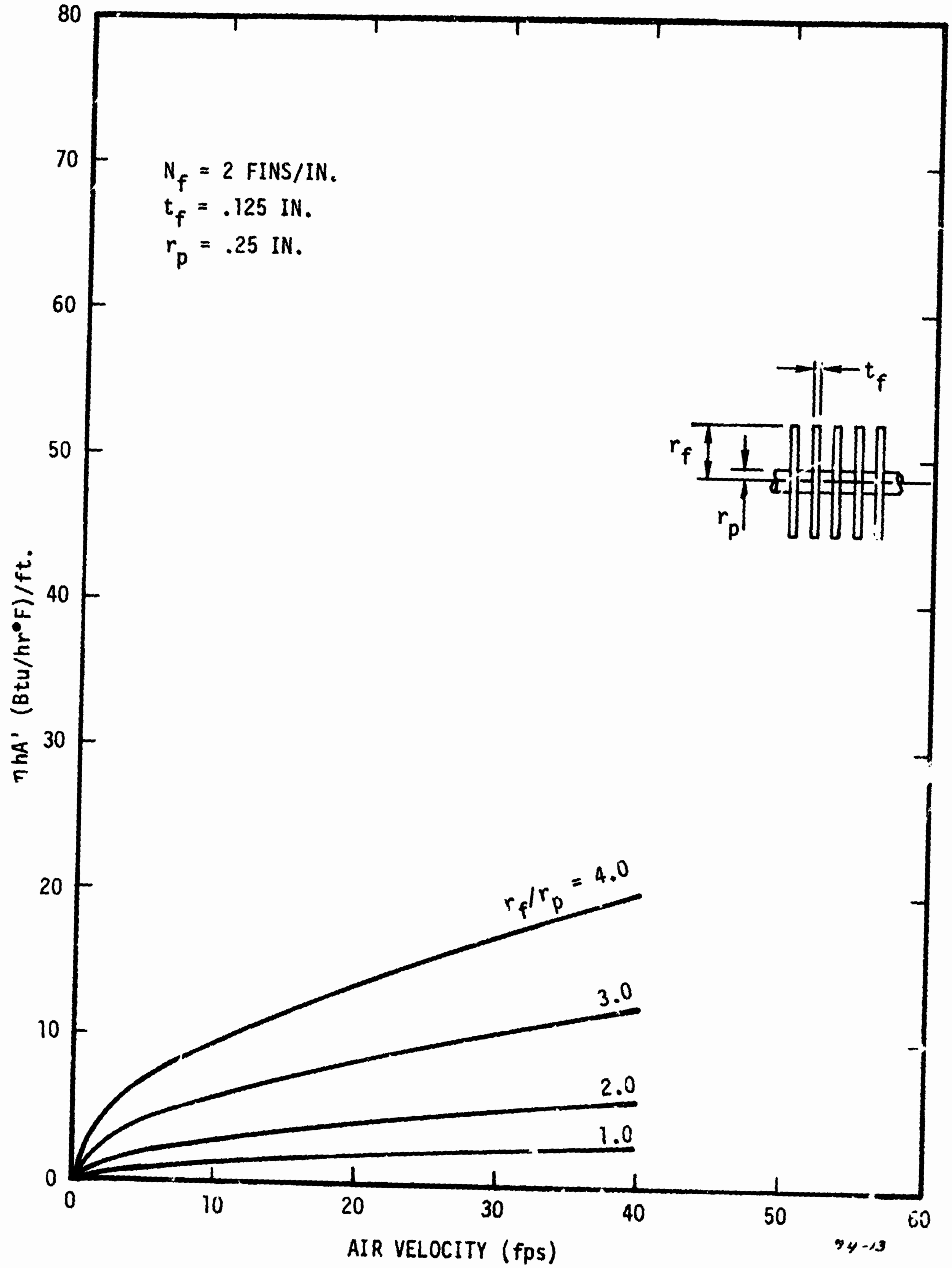


Figure 32. Air-Side Conductance for Finned Tubes

merely improving the thermal conductance between the equipment and the cooling air only the selection of the heat pipes will be discussed in this section.

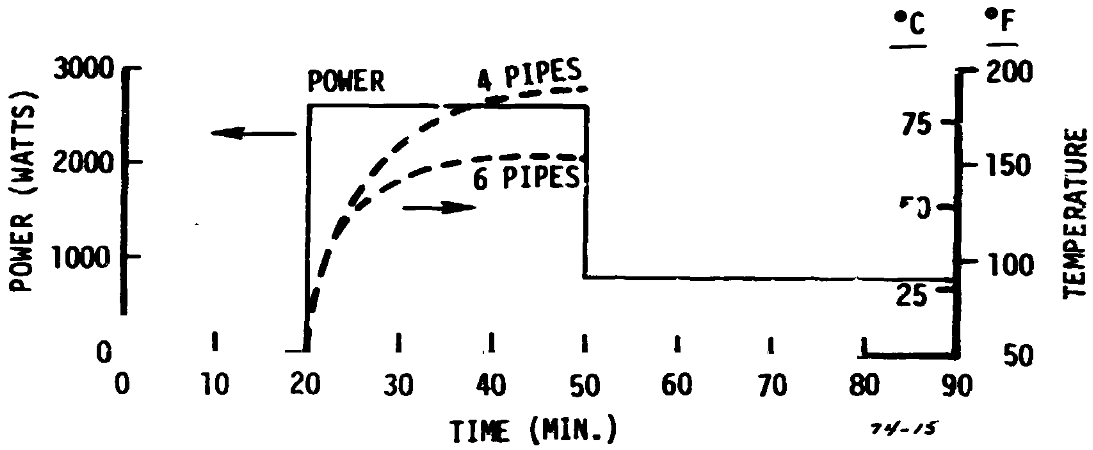


Figure 33. Estimated High Voltage Power Conditioner Temperature Profiles

Since there isn't any requirement to optimize the heat pipe for each piece of SPA equipment, an examination of the maximum heat dissipation case will suffice to select a heat pipe configuration. The high voltage power conditioner represents the highest heat dissipation of the rack-mounted electronic equipment. As shown in Figure 33, the power dissipation profile shows an initial level of 2600 watts for 30 minutes followed by 800 watts for the remainder of an experiment cycle. Since the thermal time constant for this piece of equipment is approximately 17 minutes (Ref. Table 17) the heat pipes will respond to the first 30 minute power dissipation level. Accordingly, the number of heat pipes selected must be capable of handling the 2600 watt load.

To select a heat pipe some physical aspects of the heat pipe need to be established and the appropriate wick selected. Based on the size of the equipment in the SPA payloads, the heat pipe physical geometry specified in Table 18 is selected for the heat pipe.

The heat transport by the heat pipe is limited by the heat rejection to the air by the cooling fins, therefore, a cooling fin must be selected. Examination of a 2.5-cm-radius (1-in-radius) fin at 12 fins per inch appears to provide good heat transfer for low velocities 3m/s (10 ft/s). For this fin:

$$hA' = \begin{array}{l} 330 \text{ Watts}/(C \cdot m) \\ [38 \text{ Btu}/(hr \cdot F \cdot Ft)] \end{array} \quad \text{(Figure 32)}$$

Thus the maximum heat transport in a single heat pipe is from equation (1)

$$Q = \frac{38}{3.415} \left(\frac{6}{12}\right) (150\ F - 75\ F) = 418 \text{ watts}$$

and

$$QL_{eff} = 209(18) + 418(6) + 209(6) = 7524 \text{ watt-inch (or 19,100 watt-cm)}$$

Therefore, the low voltage conditioner requires six heat pipes which will provide the temperature response shown in Figure 33. The wick selection must be based on meeting the QL_{eff} of 19,100 watt-cm (7524 watt-inches) requirement based on the selected working fluid. Because the heat pipes will be internal to the Spacelab and not subjected to temperature below the freezing point of water, water is the recommended working fluid. Water is compatible with copper and monel, but it does require oxidized surfaces for good wetting. It is believed that within the next five years water heat pipes will be well developed.

The wick selection should be based on the simplest wick that will satisfy the requirements. The homogeneous wick represents the simplest geometry and in addition are much cheaper and more reliable than arteries. The porosity, ε, of most wicks is on the order of 60 % and the wire size, δ, is determined by the need for testing in a gravitational field. It was found that a wire diameter as large as 0.05 cm (0.02 in.)

Table 18

Heat Pipe Sizing Parameters

Heat Pipe	
Diameter	1.3 cm (0.5 in.)
Evaporator length	46 cm (18 in.)
Adiabatic length	15 cm (6 in.)
Condenser length	15 cm (6 in.)
Component*	
Max temperature	66 C (150 F)
Weight	41 kg (90 lb_m)
Cooling Air	
Inlet temperature	24 C (75 F)
Velocity	3.1 m/s (10 fps)

*Power Conditioner

could be used, based on an out of level or tilt capability of as much as 1.3 cm (0.5 in.). For purposes of analysis, however, a nominal wire diameter of 0.025 cm (0.01 in.) was selected. For a 1.3 cm (0.5 in.) O.D. tube the maximum wick diameter would be on the order of 0.8 cm (0.3 in.). This corresponds to an area, A_w, of 0.45 cm^2 (0.07 in^2), which is about the same as a slab wick that is 0.38 cm (0.15 in.) thick. From Figure 28 the available heat transport capability for water at 66 C (150 F) is:

$$QL_{eff} = (220{,}000)(.07)$$
$$= 15{,}400 \text{ watt-in.}$$
$$\text{or } 39{,}100 \text{ watt-cm}$$

This design was analyzed using MULTIWICK and it was found that taking the vapor loss into account drops the available capacity to 27,200 watt-cm (10,700 watt-in.), which is more than adequate. Thus, a homogeneous wick will suffice for this application.

4.2.3.3 System Feasibility

The heat-pipe-system approach permits the use of standard commercial equipment in the absence of natural convection cooling with a minimum amount of modification or rework. It is believed that conducting the heat to a forced air duct behind the racks with heat pipes as illustrated is more efficient than providing each component with a fan or special ducting. In summary, heat pipes provide the following advantages for the Spacelab application:

- Utilization of commercially available equipment in the absence of natural convection.
- Minimum rework of commercially available equipment.
- Maximum flexibility for installation and removal of equipment at end of mission.
- Efficient cooling of electronics.

Again, as with the air-cooling and pumped-liquid-loop concepts, a total system analysis must be conducted to assure complete system feasibility. Also, a heat-pipe system (heat pipe(s) on a commercial piece of equipment) should be built and tested in an air cooling duct to demonstrate performance,

provide system pressure drop data and develop rack-mounting techniques, however, the preliminary analysis discussed herein indicates system feasibility.

4.3 EQUIPMENT THERMAL CONTROL REQUIREMENTS

The SPA payload equipment thermal control falls into two categories. The first category contains that equipment that can be thermally controlled by the basic SPA TCS. This category includes the majority of the equipment and has been discussed in previous paragraphs. The second category contains the equipment, such as high temperature furnaces, that requires internal cooling.

4.3.1 Water Cooled Equipment

There a number of items in the various SPA payloads investigated that require internal cooling because of their design. Table 19 contains a compilation of those units identified to date. As indicated, the units are generally cooled with water circulating through internal channels or cooling coils. The units are usually connected to facility water supply at 410 kN/m^2 (60 psig) which supplies the required water flow rate. Since the Spacelab does not provide a general purpose, pressurized water supply, other means of supplying the necessary cooling will have to be provided.

It is proposed that those items of SPA payload equipment requiring water cooling be equipped with a water pump (approximately 200 watt power requirement) and a heat exchanger to provide a closed loop cooling system. The heat exchanger will be a liquid to liquid type which would interface with the Spacelab water loop as shown in Figure 34. Manual valves are recommended to allow the supply lines to the SPA equipment loop to be shut off manually in the absence of the SPA payload. The Spacelab loop pressure drop characteristic should be examined to assess the need for a pressure drop simulator when the SPA heat exchanger is not on line. In the event a simulator is required the manual valves could be eliminated.

SPA payloads have been identified which require the use of an auxiliary power and heat rejection kit (Ref. Section 3.1.2). For those payloads containing items that need water cooling the heat rejection will be provided by the kit (see Section 2.4). In those instances, the SPA water cooled equipment loop will interface with a heat exchanger in the

Table 19. Internally Cooled Equipment

SPA SUBELEMENT	EQUIPMENT NAME	REMARKS
METALLURGY	HOT WALL FURNACE	INTERNAL WATER COOLING
LEVITATION	HEATER SOURCE* HOT WALL TUBE FURNACE	WATER COOLED INTERNAL WATER COOLING
CRYSTAL GROWTH	GENERAL PURPOSE FURNACE	DOUBLE WALL WITH IMBEDDED COOLING COILS - WATER COOLED
PHYSICAL PROCESSES	DYE LASER/FLASH LAMP	

* MAY BE ANY OF THE FOLLOWING TYPES

INDUCTION COILS
ELECTRON BEAM
LASER
MICROWAVE

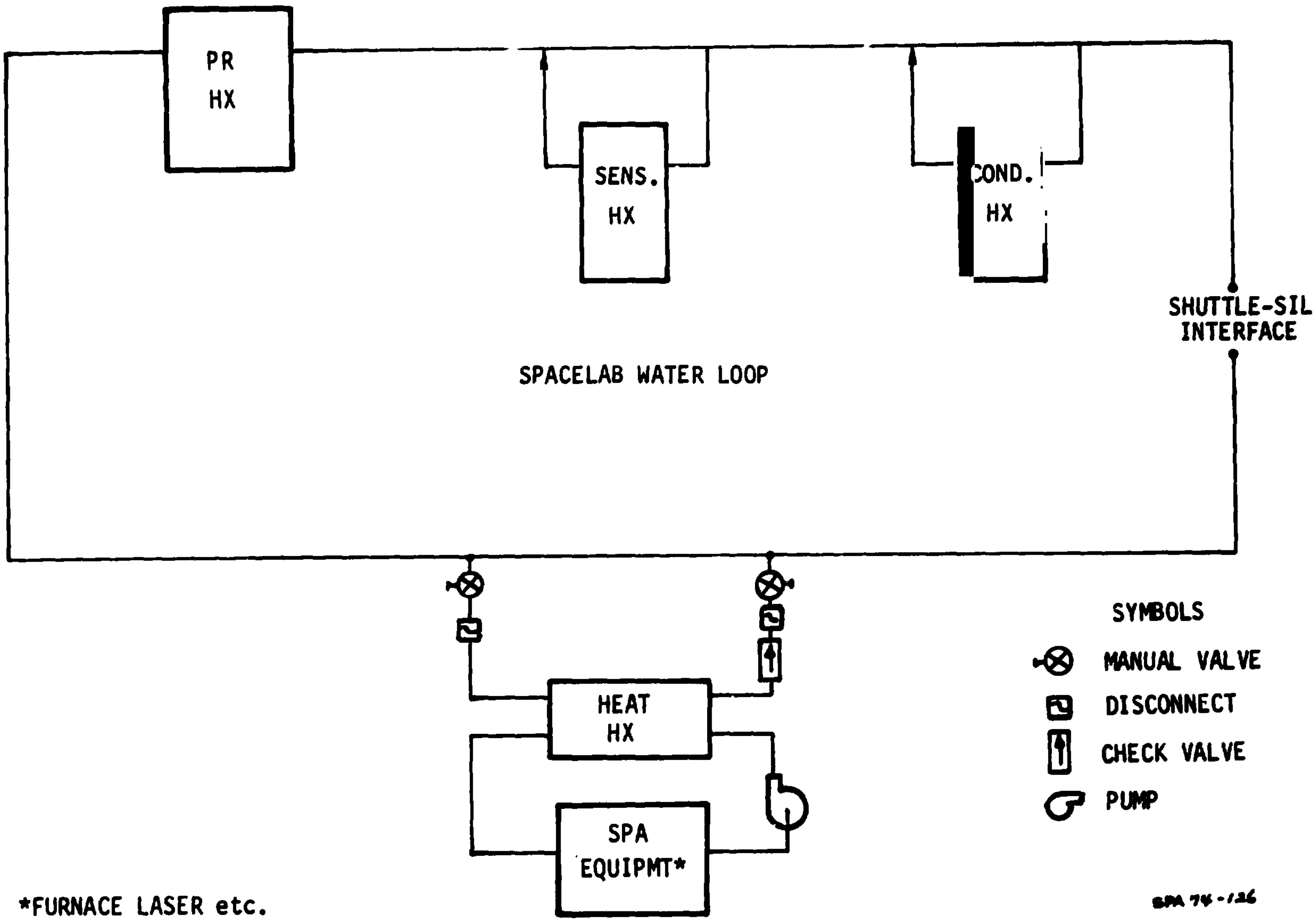


Figure 34. SPA Water Cooled Equipment Coolant Loop

kit and there will not be any interface with the Spacelab water loop.

4.3.2 Air Cooled Equipment

In addition to the rack mounted electronics, there are other SPA payload equipment requiring air cooling (notably the refrigeration equipment). Since the refrigerators or freezer units already contain, or can be equipped with, fans for the condenser heat exchanger no additional provision is required. However, since the condenser heat load will be rejected directly to the Spacelab cabin air, the cabin heat exchanger will experience a short duration transient load of as much as five kilowatts for one hour. This load must be assessed relative to Spacelab thermal control system capacity on a transient basis to determine the effect on cabin air temperature.

4.4 THERMAL CONTROL SUBSYSTEM OF POWER/HEAT REJECTION KIT

The thermal control subsystem is designated the task of maintaining the environment of the experimental modules and payload equipment with specified temperature limits during the entire mission. Heat dissipation is accomplished by systems that combines cold plates, fans, heat exchanger, pumps, accumulators and related tubing and controls.

4.4.1 System Description

The Power/Heat Rejection Kit (PHRK) thermal control subsystem (TCS) consists of a pumped liquid loop which rejects thermal energy to space via a thermal radiator located on the exterior of the PHRK structure. A simplified schematic of the TCS is shown in Figure 35. As shown, the system is a liquid loop using two radiators to reject the thermal energy absorbed from the fuel cells, electronic equipment and furnace. The primary radiator is a high temperature radiator for high heat rejection and the secondary radiator is to provide temperature drop in approximately ten percent of the flow for cooling room temperature operating electronic equipment.

Since the area available for radiators will always limit the waste heat rejection rate available to the high heat dissipating SPA payloads (e.g., Furnace Subelement Experiments), a thermal capacitor is included in the system downstream of the primary radiator. The capacitor

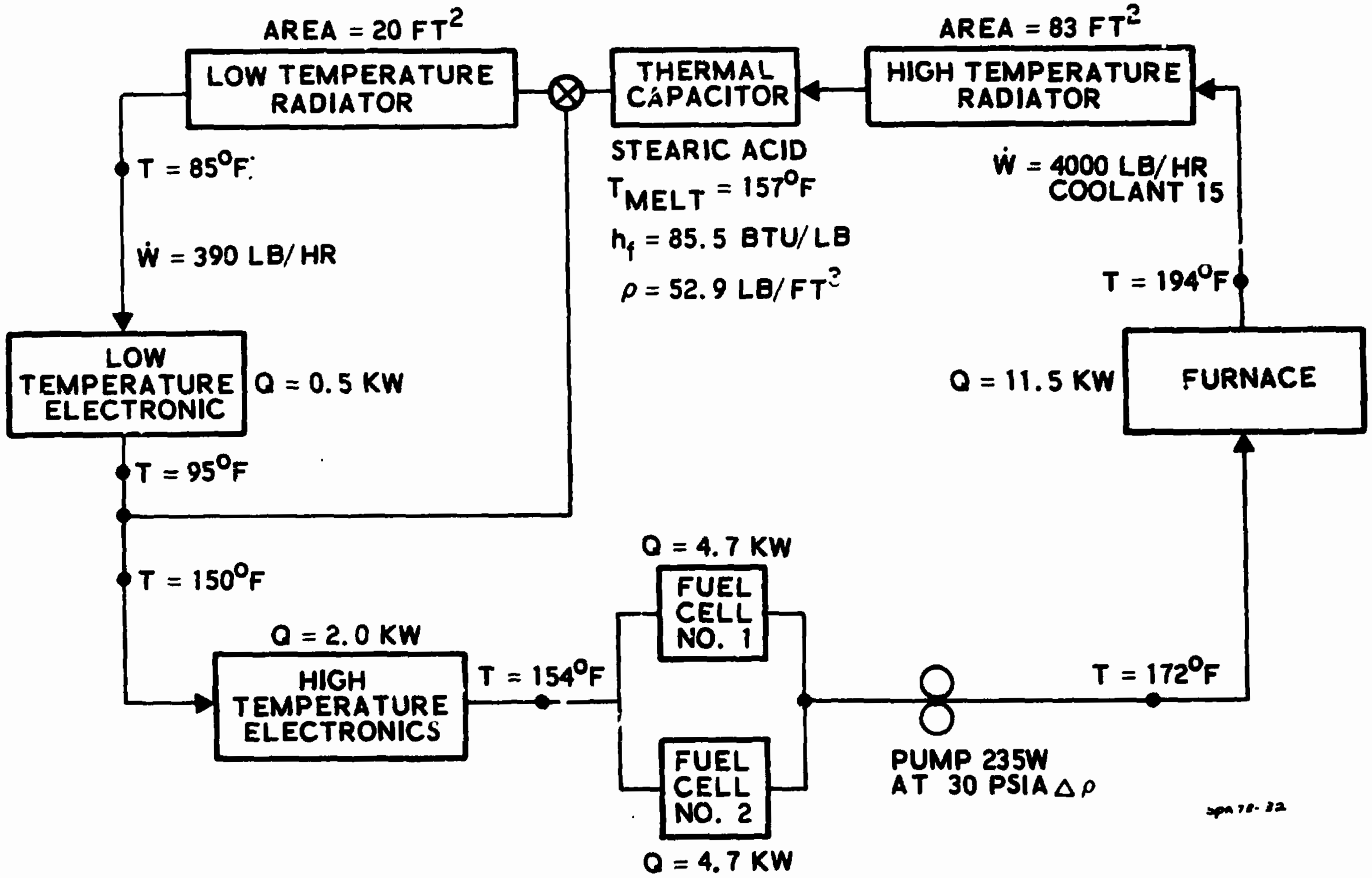


Figure 35. Power/Heat Rejection Kit Heat Dissipation System

serves the function of storing the thermal energy that exceeds radiator capacity until such a time as the thermal load falls within radiator capability. At this time the thermal energy is removed from the capacitor and rejected to space through the radiators.

Figure 35 shows the PHRK TCS for the autonomous kit operation. For those missions where the kit is in support of SPA payloads within the Spacelab, the furnace and electronics portions of the coolant loop would be replaced with interface heat exchangers to provide cooling (Figure 36). These heat exchangers would be liquid-to-liquid type where the Spacelab coolant would be water (or another suitable coolant). It is desirable to keep Coolanol 15 from the inhabitable area of the Spacelab where furnace temperatures could exceed 71 C (160 F) due to the fire hazard associated with the relatively low auto-ignition point of the Coolanol.

4.4.2 System Analysis

A system thermal analysis was conducted to assess the capabilities of the system described in the previous section. The pertinent parameters of the analysis are shown in Figure 35. A system flow rate of 1810 kg/hr (4000 lb/hr) was selected to maintain a relatively uniform temperature in the primary radiator to maximize radiator effectiveness. This high mass flow rate results in a high pump power requirement as shown on the figure.

The thermal capacitor characteristics chosen for the analysis are those of stearic acid which is a likely phase-change material for this type of system. It may prove desirable to select various phase-change materials depending upon the particular mission to be flown (i.e., autonomous or Spacelab support role for the PHRK).

Based on the heat dissipations shown in Figure 35, the thermal control system heat rejection is shown in Figure 37. For the purpose of the analysis, the electrical power was assumed to be an instantaneous thermal load. In reality, the thermal mass associated with the electrical power dissipators will tend to reduce the peak load and/or shorten its expressed duration. The system heat rejection (expressed as allowable duty cycle for the electrical load) is shown for the baseline system and the addition of a water evaporator which utilizes the fuel cell water. Also shown is the effect of radiator sink temperature which can materially increase the allowable peak power duty cycles.

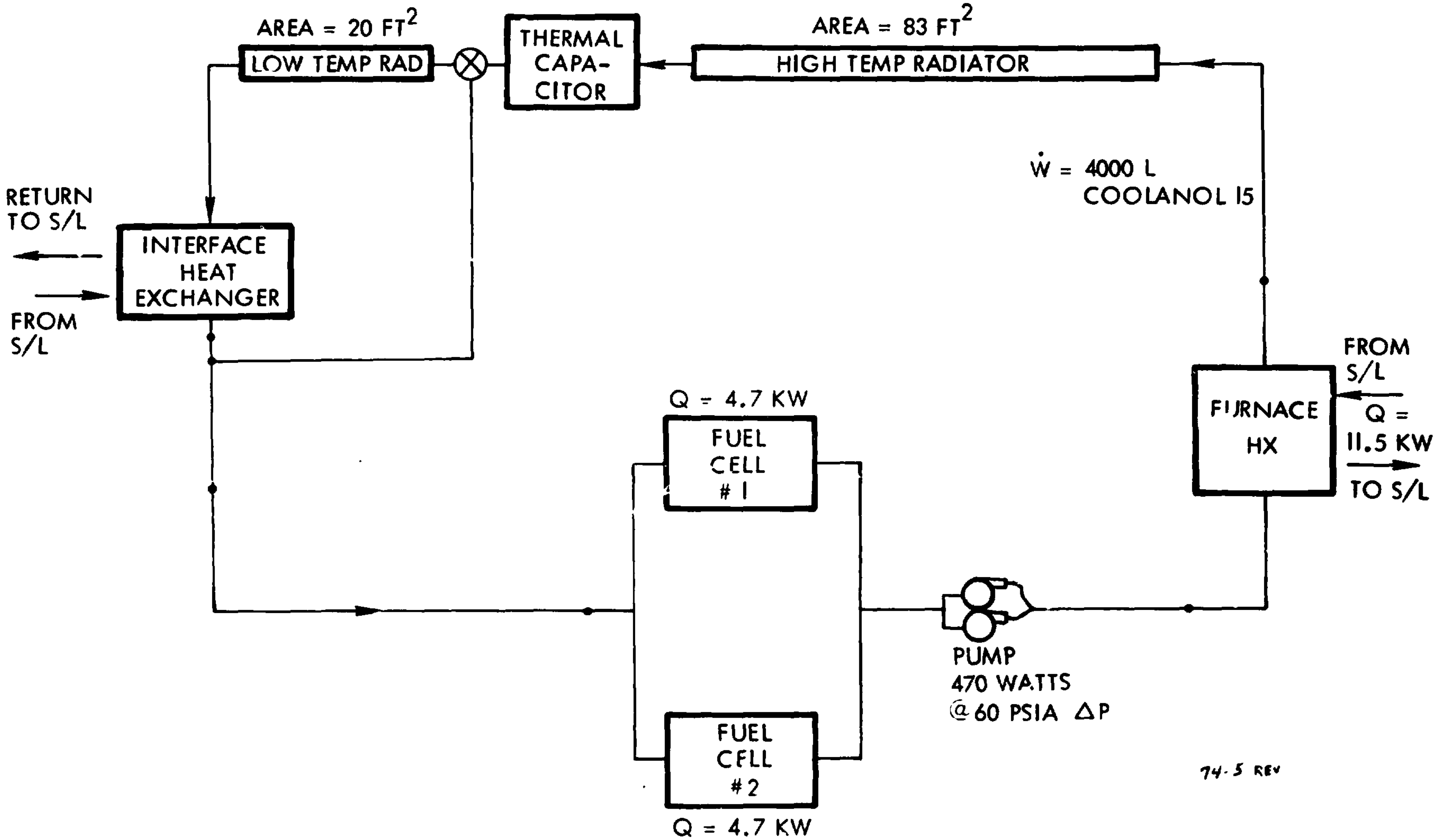


Figure 36. Power/Heat Rejection Kit's Heat Dissipation System (Internal Spacelab SPA Payloads)

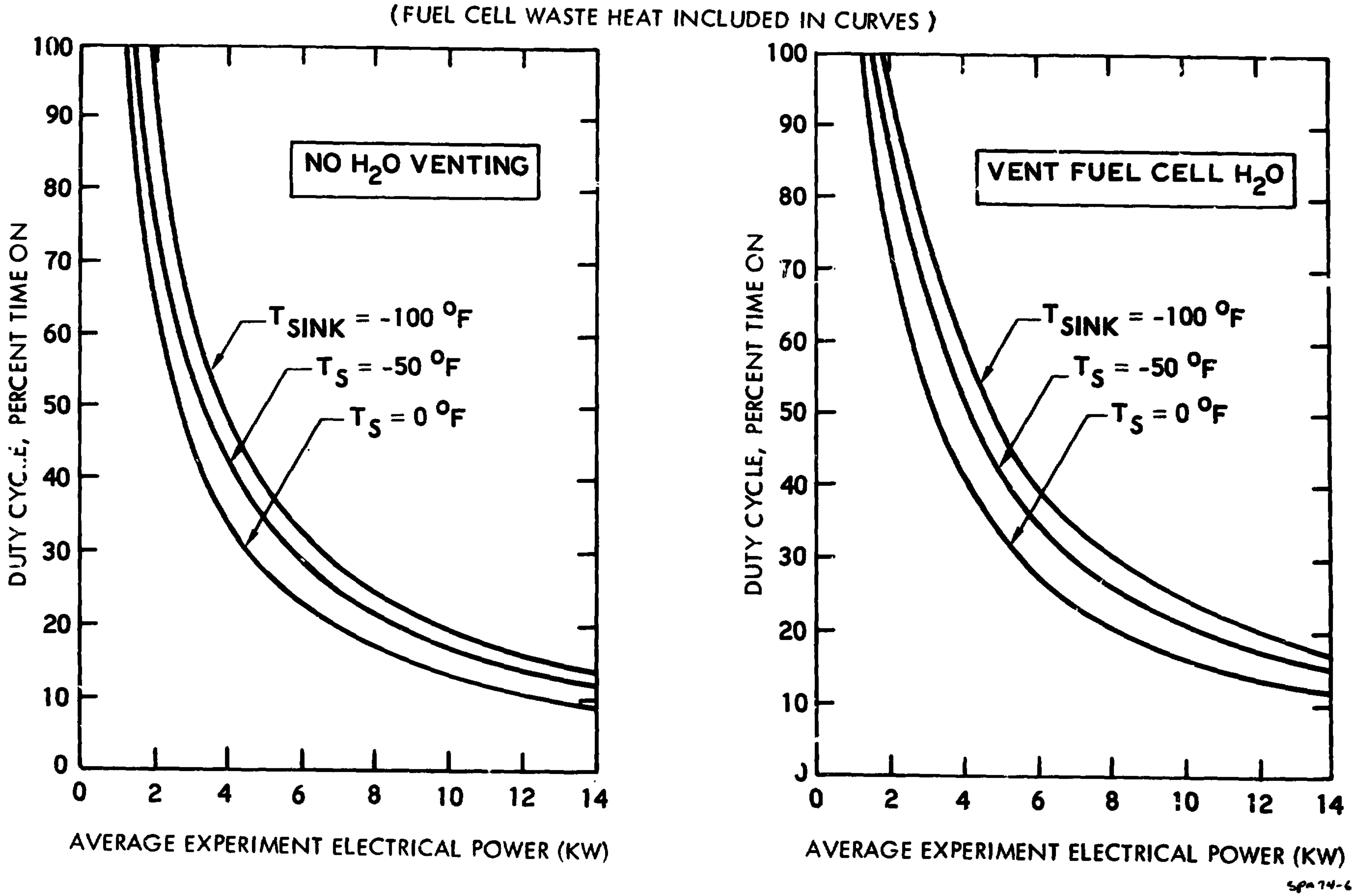


Figure 37. Allowable Duty Cycle for Kit

Since the TCS capability is based on use of a thermal capacitor, the volume (or mass) of phase-change material can be varied to increase operating times for peak loads. The required weight (not including container) is shown in Figure 38. For example, to obtain a capability of a 4 kW peak for 30 minutes requires 45 kg (100 lb) of heat sink material. Additional operating time can be obtained for a 4 kW load at the rate of 1.5 kg (3.3 lb) of phase-change material per additional minute of operation.

If it is assumed that the inherent thermal mass of the PHRK is such as to increase the allowable duty cycle by a factor of 2 for short duration peak/loads (< 2 hrs.) conducting a furnace subelement experiment (typical power profile shown in Figure 39) would require a thermal capacitor of approximately 227 kg (500 lb). If stearic acid is used as the phase-change material, approximately 0.25 m^3 (9 ft^3) of material is required. This mass can be reduced to 181 kg (400 lb) if the fuel cell water is utilized in an evaporator system integral with the TCS loop.

Table 20 gives a weight estimate of thermal capacitor required in the PHRK to meet the various experiment heat dissipation requirements for limiting case assumptions. Table 20, as such, illustrates the heat rejection capacity as the preeminent limiting interface subsystem. Stearic acid with a heat of fusion of 199 J/g (85.5 Btu/lb) was assumed as the capacitor material. Capacitor weights were calculated for autonomous operation of the PHRK and for the case where 4.8 kW electrical equivalent heat is dissipated by the Spacelab. Also, the effect of venting fuel cell water with an evaporator is shown. The cases where zero capacitor weight is shown indicates that the PHRK can handle the required thermal load in a steady state mode. For all other cases the experiment repeat frequency must be constrained to allow the thermal capacitor material to re-solidify. The repeat frequency can be determined from the duty cycle curves shown in Figure 38.

The requirement for thermal capacitor mass can be reduced by allowing heat leak from the PHRK structure to the Shuttle bay structure. With the Shuttle bay doors open the bay structure approaches -73C (-100 F). For a PHRK structure temperature of 38 C (100 F) approximately 6 kW of thermal heat leak can be generated. This is equivalent to 110 kg (245 lb) of phase-change material on line for one hour. Another means of reducing the

Table 20. Thermal Capacitor Weight Requirements

PAYLOAD NO.	THERMAL CAPACITOR WEIGHT							
	NO REJECTION BY SPACELAB				4.8 KW REJECTED BY SPACELAB			
	NO H_2O VENT		VENT FC H_2O		NO H_2O VENT		VENT FC H_2O	
	kg	lb	kg	lb	kg	lb	kg	lb
1	675	1490	571	1260	219	482	162	356
2	1010	2220	812	1790	380	836	282	620
3	2330	5130	1880	4130	1290	2840	1020	2250
4	795	1750	653	1440	0	0	0	0
5	695	1530	558	1230	316	695	240	530
6	1100	2430	880	1940	465	1025	354	780
7	252	555	200	440	0	0	0	0
8	366	805	288	635	0	0	0	0
9	239	527	184	405	0	0	0	0
10	476	1050	368	810	0	0	0	0
11	191	420	148	325	0	0	0	0
12	467	1030	361	795	0	0	0	0

Note: Based on -73C (-100F) sink temperature.

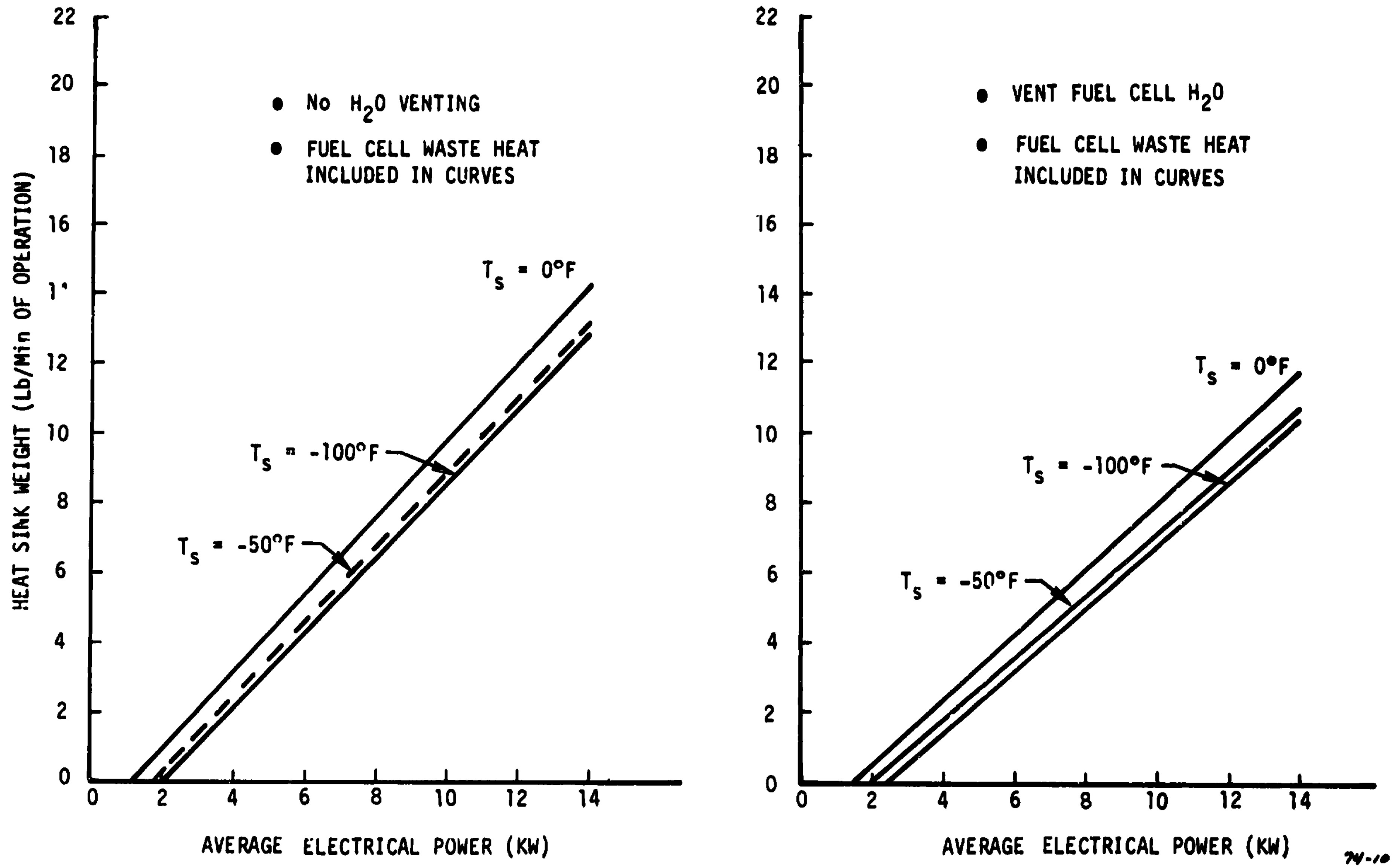
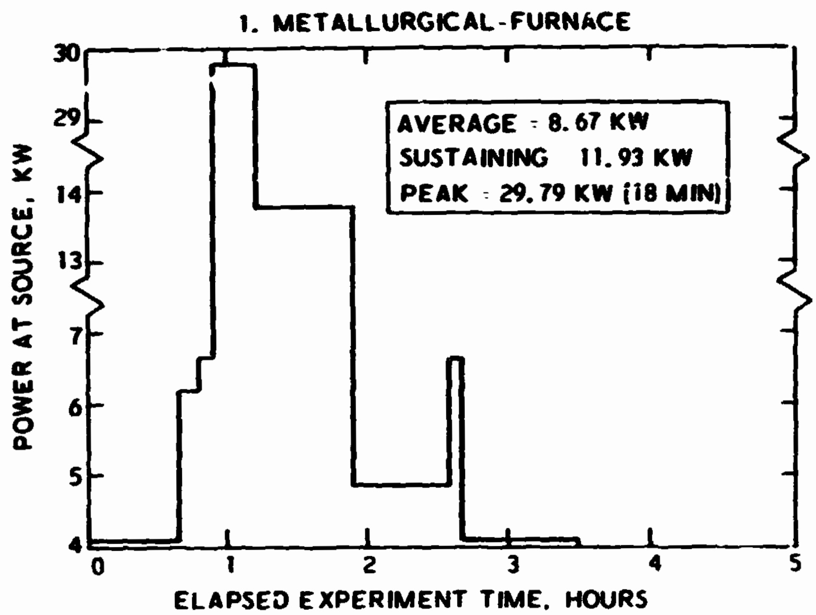


Figure 38. Required Heat Sink Material Weight



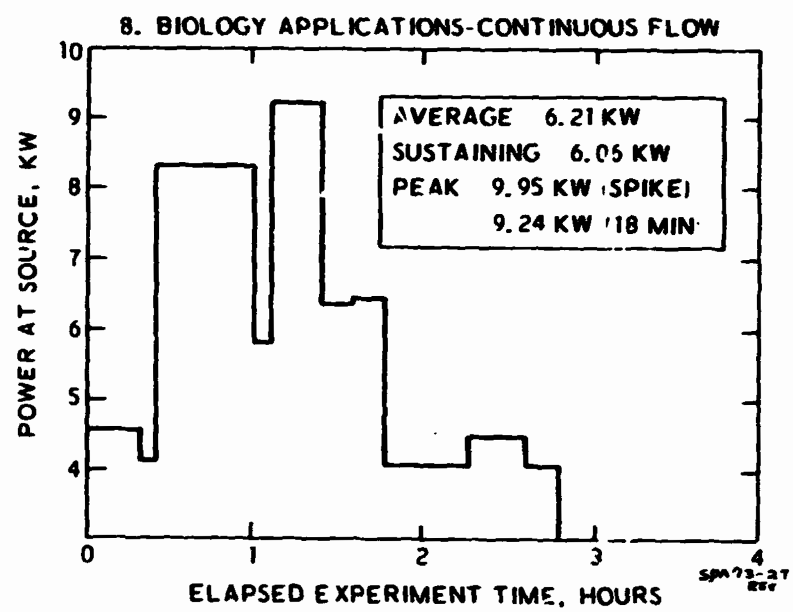


Figure 39. SPA Experiment Power Source Load Profiles

capacitor mass requirement would be to use a material with a higher Joule/gram (Btu/lb) rating. Materials are in existance with values as high as 278 - 302 J/g (120 - 130 Btu/lb) that change phase in the 66 C (150 F) temperature range. However, all the characteristics of these materials have not been thoroughly studied to date.

Further definition of equipment to be included in the PHRK (notably electronics) may allow the radiator to operate at higher temperatures. The heat rejection as a function of fin root temperature is shown in Figure 40. If electronic temperatures are allowed to operate at 74 C (165 F) or above, less thermal capacitor material would be required.

4.4.3 Radiator Sizing

The feasibility of providing a heat rejection capability to allow the PHRK to operate at a steady state electrical load of up to 14 kW was investigated. The radiator area requirements were established as a function of the fuel cell stack's coolant exit temperature because the fuel cell's coolant temperature is a principal parameter affecting the radiator design.

To fully validate the system defined herein, further detailed thermal analyses of the radiator heat rejection and evaluation of the coolant loop fluid and pump requirements will be required. In order to achieve a radiator system of high heat rejection density, portions of the coolant loop must operate at temperatures in excess of 370 C (700 F). This operating temperature level requires high system operating pressures and special considerations for line connections and seals.

4.4.3.1 System Definition

The requirement to provide cooling for up to 14 kW of consumed electrical power results in a radiator heat rejection requirement of up to 23.5 kW. The additional 9.5 kW of thermal energy comes from the fuel cell waste heat as shown in Figure 16 of Section 3.1.2. For the purposes of PHRK radiator sizing, the Pratt and Whitney fuel cell characteristics were chosen based primarily on the higher coolant exit temperature of the unit. The 14 kW electrical output is made up of two fuel cells operating at the 7 kW output level. The electrical output power is supplied to SPA payload equipment and is subsequently rejected as waste heat within the

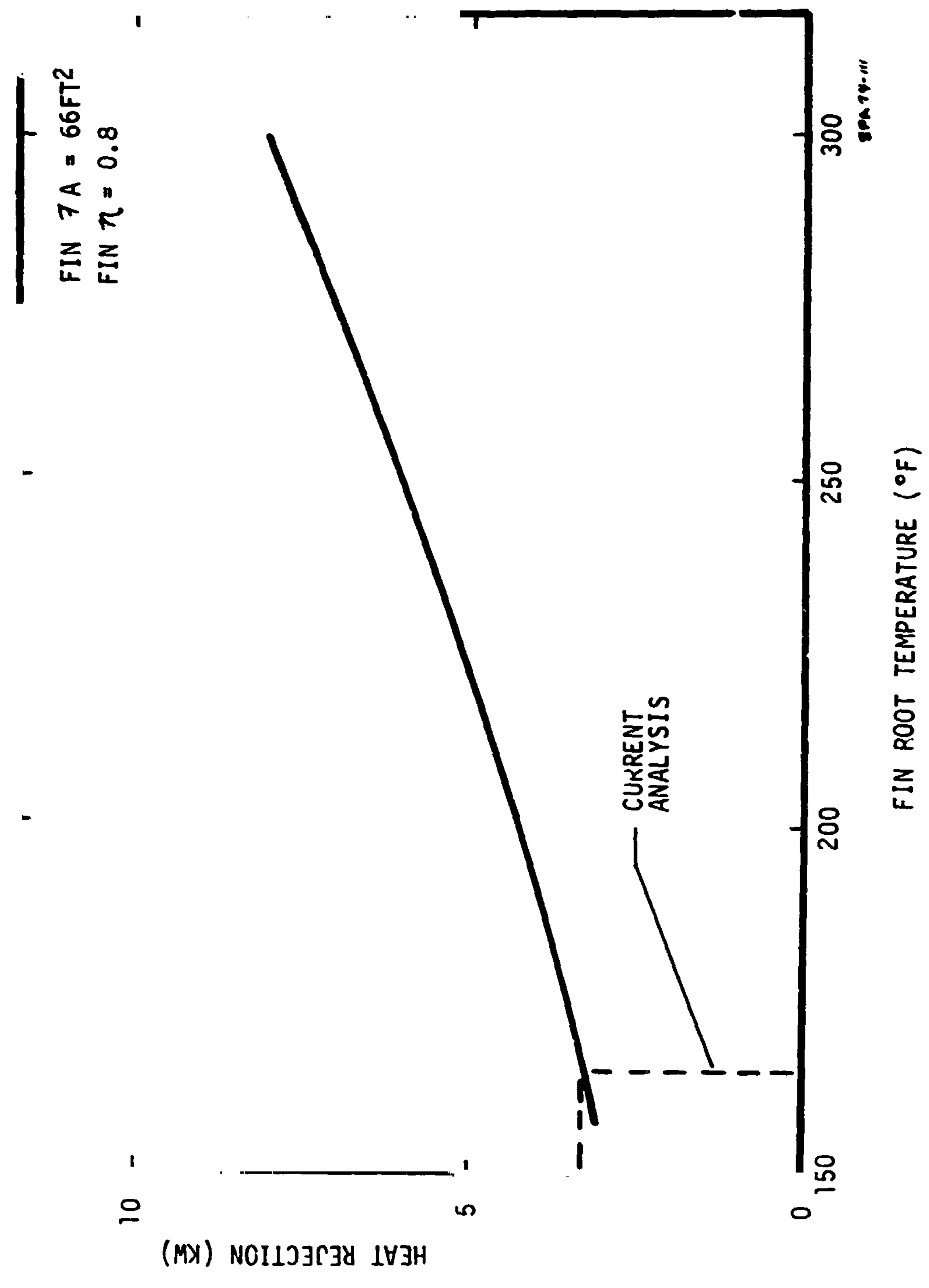


Figure 40. Radiator Heat Rejection

thermal control loop (TCL). For the purpose of TCL definition, the waste heat load sources were assigned as shown in Table 21.

As shown in Table 21, various load sources also have maximum allowable temperature requirements. The allowable temperatures listed in Table 21 were assigned as possible levels for TCL system definition purposes. Considering both the heat load sources and the associated temperature levels a TCL similar to the schematic shown in Figure 41 is required. The radiator arrangement features three separate radiator sections. The high temperature section provides for rejection of the waste heat from high temperature qualified equipment which provides for a high heat rejection density and also minimizes the radiator area. However, to achieve the high inlet coolant temperature necessary for this radiator requires that a portion of the total flow be diverted through this section of the TCL. Attendant with this necessary lower coolant flow rate will be a large temperature drop across the radiator. The temperature drop is such that achievement of sufficient radiator effectiveness ($\eta \approx 0.6$) will require subsectioning the radiator with radiator and bypass mixing of the coolant.

The second radiator section (moderate temperature) provides for rejection of fuel cell waste heat with a radiator outlet temperature compatible with the fuel cell cooling requirements. Since the area of this radiator is coupled to the fuel cell waste heat rejection and temperature requirements, it becomes the governing radiator for total system radiator area requirements. To minimize the temperature drop in this radiator (necessary for a reasonable effectiveness; $\eta \approx 0.8$) the total system flow is passed through the radiator after being mixed with the effluent from the high temperature radiator.

A third radiator section provides the necessary temperature drop in a portion of the flow to allow cooling of low temperature electronics. The exit coolant from the low temperature electronics heat exchanger is mixed with the outlet of the secondary radiator (moderate temperature) to allow total system flow through the fuel cell heat exchangers.

4.4.3.2 System Performance

The total radiator requirement is directly dependent upon the limiting fuel cell operating conditions, specifically the fuel cell coolant exit

Table 21. Power and Heat Rejection Kit Thermal Load Sources

Source	Waste Heat (kW)	Max. Temp. Level [C (F)]
Fuel Cells (2)	9.5	Study Variable
High Temperature Equipment	11.0	427 (800)
High Temperature Electronics	2.0	177 (350)
Low Temperature Electronics	0.5	71 (160)
TCL Pump(s)	0.5	177 (350)

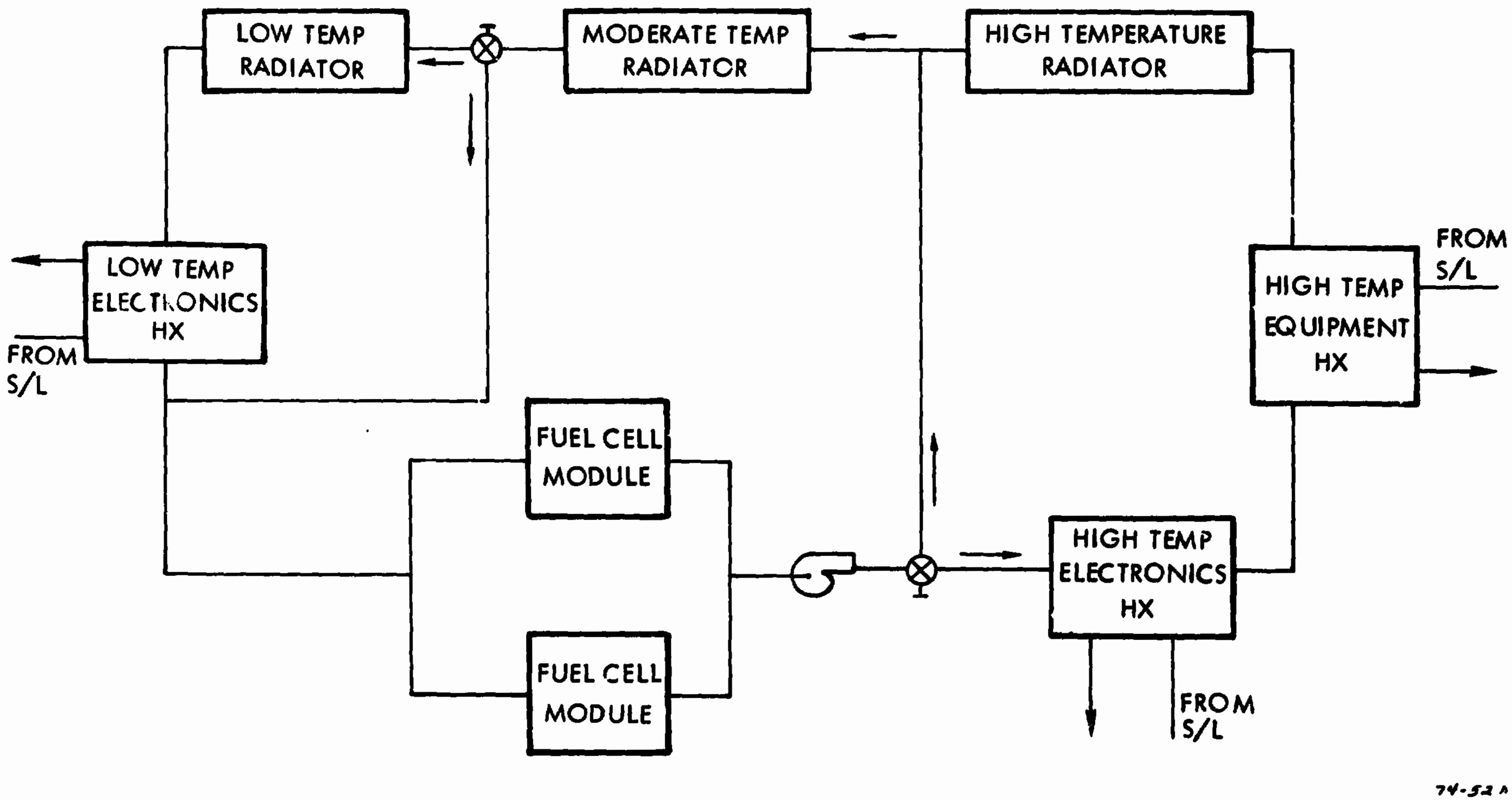


Figure 41. Power and Heat Rejection Kit Thermal Control Loop Schematic

temperature (Te) (see Figure 12, Section 3.3.2). As such, the relationship between the fuel cell exit coolant temperature and PHRK radiator area is presented in Figure 42. The required radiator area when compared with the available area shows that the radiator system is limited to only one fuel cell provided the fuel cell can operate at an exit coolant temperature of 140 C (285 F) or higher. The available radiator area is based on the PHRK exposed body surface (120° arc) with a seven-foot-long radiator. A system using a deployed radiator such as shown in Figure 43 could provide for one fuel cell at nominal fuel cell temperature or two fuel cells at an exit coolant temperature of approximately 150 C (300 F). A deployed radiator such as shown in Figure 43 would necessarily require further assessment relative to the effects of shadowing portions of the shuttle radiator system (bay door radiators).

4.4.3.3 <u>System Feasibility</u>

The feasibility of the TCL described herein is predicated on many factors. As shown, major design considerations are the fuel cell's operating conditions and the available radiator area. Referring to Figure 42 and based upon the nominal fuel cell operating temperatures and the defined area for a kit/body-mounted, 120° angle radiator, the output of one fuel cell cannot be accommodated in a steady state mode of operation. For such a radiator size, a fuel cell operating temperature of between 140 C (285 F) to 143 C (290 F) would be required for a one-cell system. Feasibility of operating candidate shuttle-type fuel cells at this temperature level must still be assessed.

Two fuel cells operating continuously requires a substantial increase in either the necessary radiator area or a combination of an increase in radiator area along with an increase in fuel-cell operating temperature. Any increase in radiator area impacts both shuttle and/or other payload operations and must be assessed accordingly.

Furthermore, the radiator heat rejection effectiveness must be assessed more thoroughly to validate the conceptual levels presented. The high temperatures and predicated large temperature drops of these preliminary analyses require that further detailed thermal analysis be conducted to validate overall system feasibility. As such, a coolant fluid assessment must be effected to determine to what degree high temperatures [370 - 427 C (700 - 800 F)] in part of the loop are compatible with existing

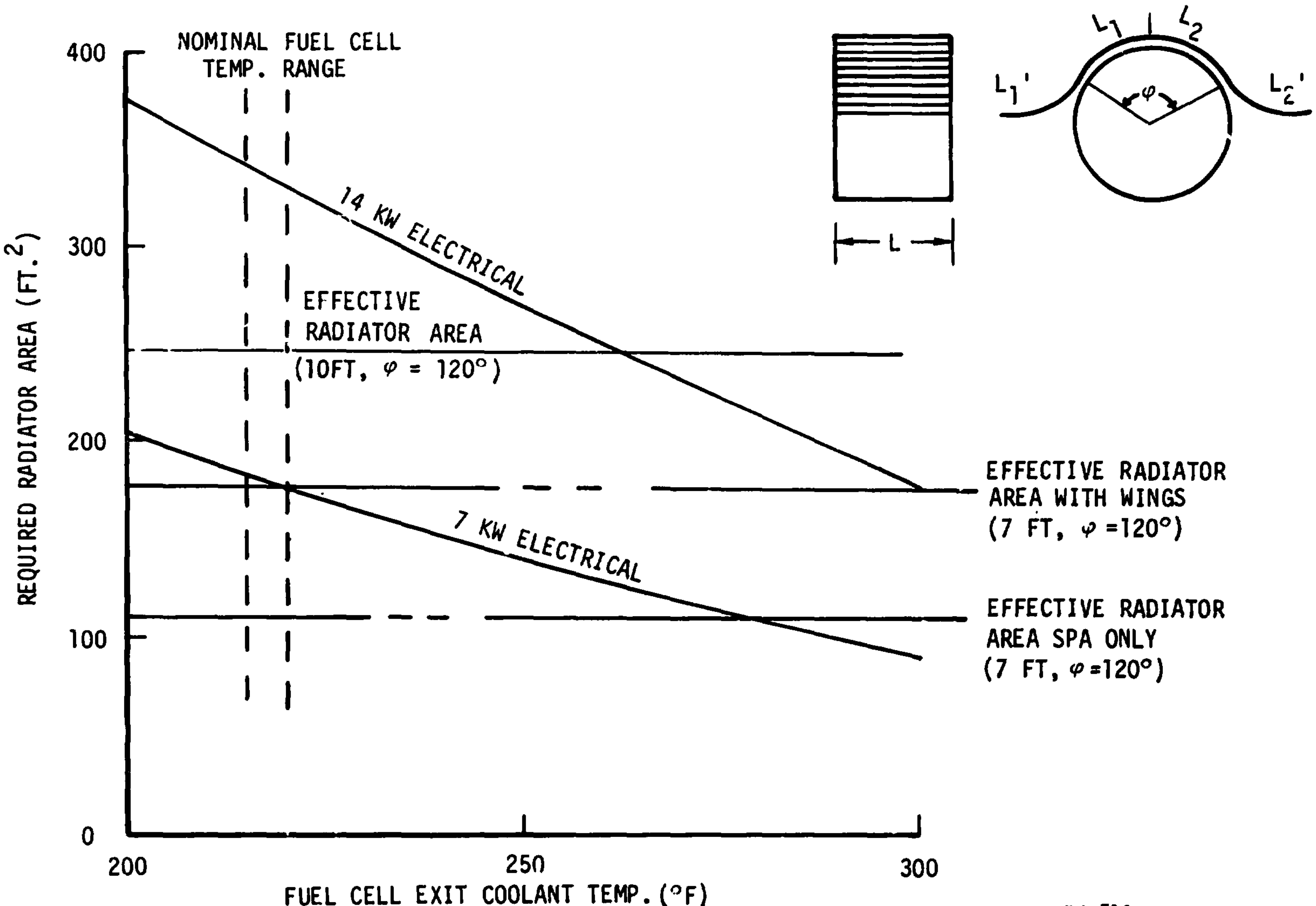


Figure 42. Power and Heat Rejection Kit Heat Rejection Capability

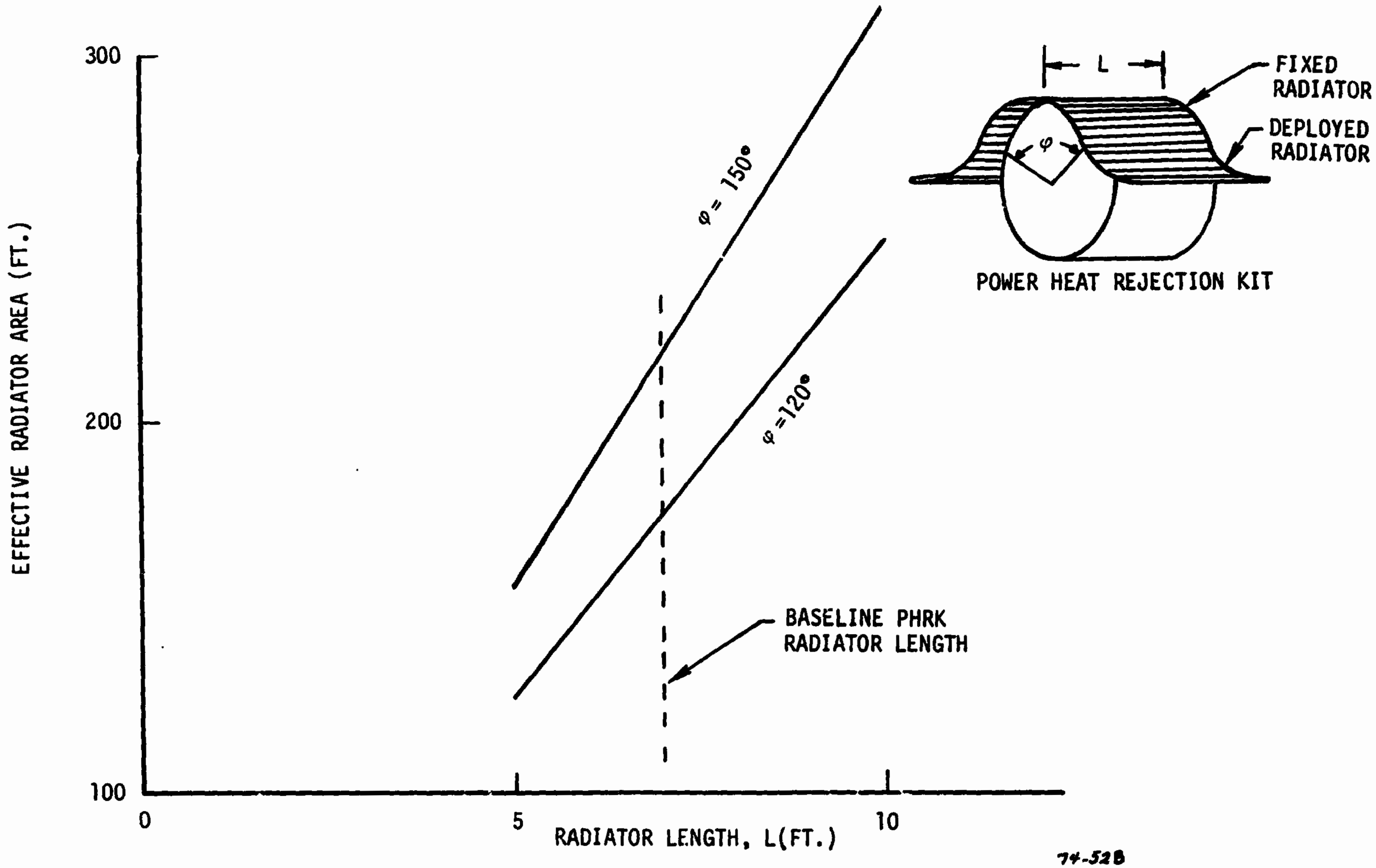


Figure 43. Power and Heat Rejection Kit Deployed Radiator

working fluids. This temperature level is near the upper limit for normally employed coolants. Dowtherm A, for example, is near its operating limit at 400 C (750 F). If a compatible fluid cannot be selected, available fluid temperature limits may become the governing parameter for radiator requirements.

The results of a preliminary system analysis as presented herein indicates that a system to accommodate the output of two fuel cells operating continuously (14 kW) is not out of the realm of possibility; however, impacts to both fuel cell design and shuttle bay radiators may result. Further detailed studies are required before a kit system and its performance ranges can be finalized.

5. ELECTROMAGNETIC COMPATIBILITY (EMC) SUBSYSTEM

The principal concern of the EMC studies related to the SPA program has been the development of a system-level approach towards establishing payload self-compatibility and compatibility with the Space Shuttle environment. The initial efforts have, therefore, been aimed at various levels of categorization of the payloads and interfacing equipment and at the establishment of initial estimates for the EMC environment for the respresentative payload configurations. The potential utilization of a computer-assisted analysis effort has been investigated and several of the key parameters for such an approach have been determined.

5.1 EMC CLASSIFICATION

The basic assumption for any system-level approach to EMC categorization is the requirement that individual components constituting such a system are at least self-compatible. This implies also that there exists some sort of a margin between the internal noise levels of the component and those noise levels which, possibly due to the external electromagnetic environment, cause the equipment performance to be degraded to undesirable levels. In addition, it must also be recognized the electrical/electronic equipment emits a certain level of electromagnetic energy as a result of its intended manner of operation. Several manners of categorization suggest themselves. One such system utilizes the concept that any component, interface circuit or subsystem can always be categorized on its electomagnetic emission characteristics (either hard wire conducted or radiated) and by its levels of susceptibility to conducted or radiated noise levels. A further level of breakdown can be accomplished by differentiating between those emissions which are related to functional processes and those which represent a spillover into the spectrum range not required for proper component operation. Potentially susceptible "circuits" can be similarly described in terms of effects due to interference within their functional range of operation and the so-called out-of-band responses. Finally, it is also necessary to categorize the process whereby the potential source of interference transfers this energy into the receiving terminal.

The following set of classifications have been selected as a working basis for the SPA EMC study. Note that these categories are not necessarily

mutually exclusive, as a component or subsystem may be a source of interference to another unit at the same time that it may be susceptible to emissions from a third unit.

5.1.1 Essential Emitters

Those physically present or specification-imposed generators of electromagnetic energy set the minimum levels for the SPA EMC environment. They include sources of conducted as well as sources of radiated emissions and are not limited to the SPA payload exclusively. The following examples fall into the class of intentional emitters:

- AC Powerlines
- Induction Heaters
- Microwave Heaters
- EMC Specification-imposed susceptibility test levels
- Space Shuttle RF transmitters

All of these sources have one principal EMC characteristic: their emission spectrum is set by functional requirements and, therefore, cannot be altered by direct suppression techniques.

5.1.2 Non-Essential Emitters

These contributors to the SPA EMC environment represent those sources of noise which are non-essential to the proper functioning of either the Space Shuttle, the Spacelab, or the SPA payload. Examples of such emitters are the following:

- Converter Ripple
- Induction Heater Harmonics
- RF Leakage and Spurious Emissions
- Switching Transients
- Flashtube Emissions
- E-Beam Instabilities

The overall EMC design of the Spacelab and SPA payload needs to effectively control these sources, but must do so in a balanced effort aimed at compatible system operation and not just specification compliance.

5.1.3 Intentional Receivers

An intentional receiver, as treated in the context of this study, is

any circuit or component receiving signals within the bandwidth required for its proper operation. These parameters are set by functional requirements and bandwidth-limiting techniques that are normally applied as desensitization methods are ruled out. Examples of such receptors are listed below:

- Analog Telemetry Channels
- Command Lines
- Communication Receivers
- Sensor Readings
- Digital Data Lines
- Video Link

As previously noted, many of these items represent the interfaces between the SPA payloads and Spacelab, or even the Space Shuttle. A considerable amount of the EMC design of the SPA payload is therefore dependent upon the ultimate configuration of the selected Spacelab design.

5.1.4 Inadvertent Receivers

The inadvertent receivers are generally identical to the categories listed above under intentional receivers. The primary difference between the two categories is the emphasis in this category upon out-of-band response. Sensitivity to interference in the frequency ranges covered by this category can be altered significantly, at least in concept, without affecting the circuit's capacity for proper operation. A few of these "receivers" are listed below:

- Image Response
- Out-of-Band Response
- Excess Bandwidth
- Non-Linearities (Rectification, Peak Detection, etc.)
- EMC Specification-allowed Interference Levels.

The last item listed above treats the allowed levels of radiated and conducted interference as if the initial unit level EMC specification criteria represented a hypothetical composite receiver.

5.1.5 Transfer Mechanisms

There exist five principal mechanisms whereby electromagnetic energy may be transferred from a source to a receiver. Again, these are not

necessarily mutually exclusive, but as a practical matter, one of the five mechanisms usually predominates.

- Common Impedance
- Mutual Inductance
- Common Capacity
- Electric Fields
- Magnetic Fields

Further breakdowns are possible in each of the individual categories, such as common source impedance and distributed ground plane resistance for the case of common impedance coupling. Also, it may become inefficient to treat two mechanisms separately (i.e., E- and H-fields of a plane wave) but if the separation can be maintained, a solution to the energy coupling calculations becomes amendable to computer analysis. A model of such a mechanization, as used in the TRW-developed SEMCAP* computer program, is shown in Figure 44. The specific transfer equations for each of the coupling mechanisms are individually stored in the core program, and only the geometric, shielding and grounding parameters need be specified as in input.

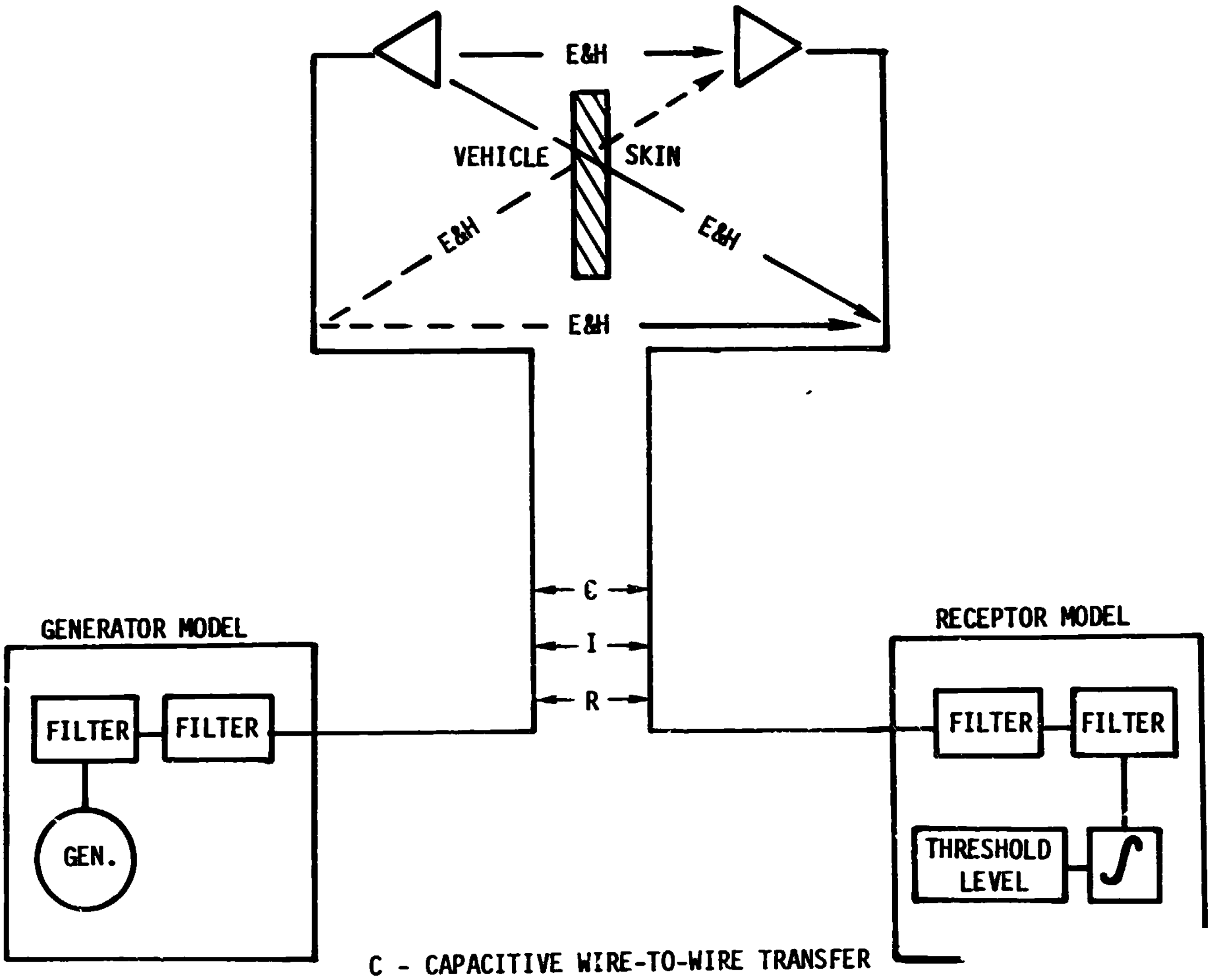
5.2 EMC CHARACTERISTICS

An initial effort has been made during the course of this study to identify the most prominent factors which will determine two potential EMC characteristics of the SPA payload and the Spacelab environment. This effort has been hampered considerably by the almost total lack of any applicable EMC data on commercial components under consideration for SPA (see section 5.3). Partly to circumvent this problem and partly also to obtain at least an order of magnitude estimate for the parameters involved, a review was conducted of the available EMC literature pertinent to the subject. In addition, an in-house test program was started to measure some of the pertinent EMC characteristics of R&D prototypes of equipment similar to that under consideration as potential SPA payloads. The results of this literature and test survey are presented in the following sections.

5.2.1 Prominent Emission Sources

Sources of potential interference are generally classified as either

*SPECIFICATION AND ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM.



C - CAPACITIVE WIRE-TO-WIRE TRANSFER
I - INDUCTIVE WIRE-TO-WIRE TRANSFER
R - COMMON RESISTANCE TRANSFER
E - ELECTRIC FIELD TRANSFER
H - MAGNETIC FIELD TRANSFER

SPA74-125

Figure 44. Computer Analysis Model

steady-state or transient and may be further subdivided into either conducted or radiated interference. Some of the more prominent emission sources for the SPA payload and interfacing equipments are identified below.

5.2.1.1 Steady-State Radiated Interference

The two most prominent sources of steady-state radiated interference among the SPA candidate payloads are the induction heater and the microwave oven. The induction heater radiated interference can be expected to be a major consideration for the design of the Spacelab data handling and communication equipment while the microwave heater, although to a much lower emission level, needs to be considered as a potential source of interference to the RF communication links of the Space Shuttle.

Line spectra radiated by induction heaters can be expected to range from 1 to 10 ampere-turns/meter (1 to 10 microteslas) at the primary induction heater frequency (tuneable from 2 kHz to 2 MHz). Harmonic emissions depend significantly upon the loading of the induction heater coil, but can be expected to roll off at approximately 60 dB/decade or better. These levels are from 60 to 120 dB above those specified in MIL-STD-1541, the USAF space vehicle amendment to MIL-STD-461A. The Space Shuttle Amendment to MIL-STD-461A as of yet does not specify any limits for magnetic field radiation above 50 kHz.

Figures 45 and 46 illustrate the levels of magnetic field radiation measured at a 1-meter distance from two separate induction heaters. It is of interest to note that the lightly loaded induction heater radiated a significantly higher level of harmonics, and that the type of power supply used for the heaters appears to have a marked effect upon the radiated levels of broadband interference. The latter conclusion has to be somewhat qualified by the fact that no tests of heater coil loading upon power supply generated noise levels were made.

A somewhat different situation exists for the microwave oven. Use of the contactless positioning system implies that the microwave cavity must be provided with "electrically thin" walls, and the electrical thickness of these walls will therefore have to be constrained to a few skin depths. Assuming a reflection loss of approximately 78 dB for the microwave signal,

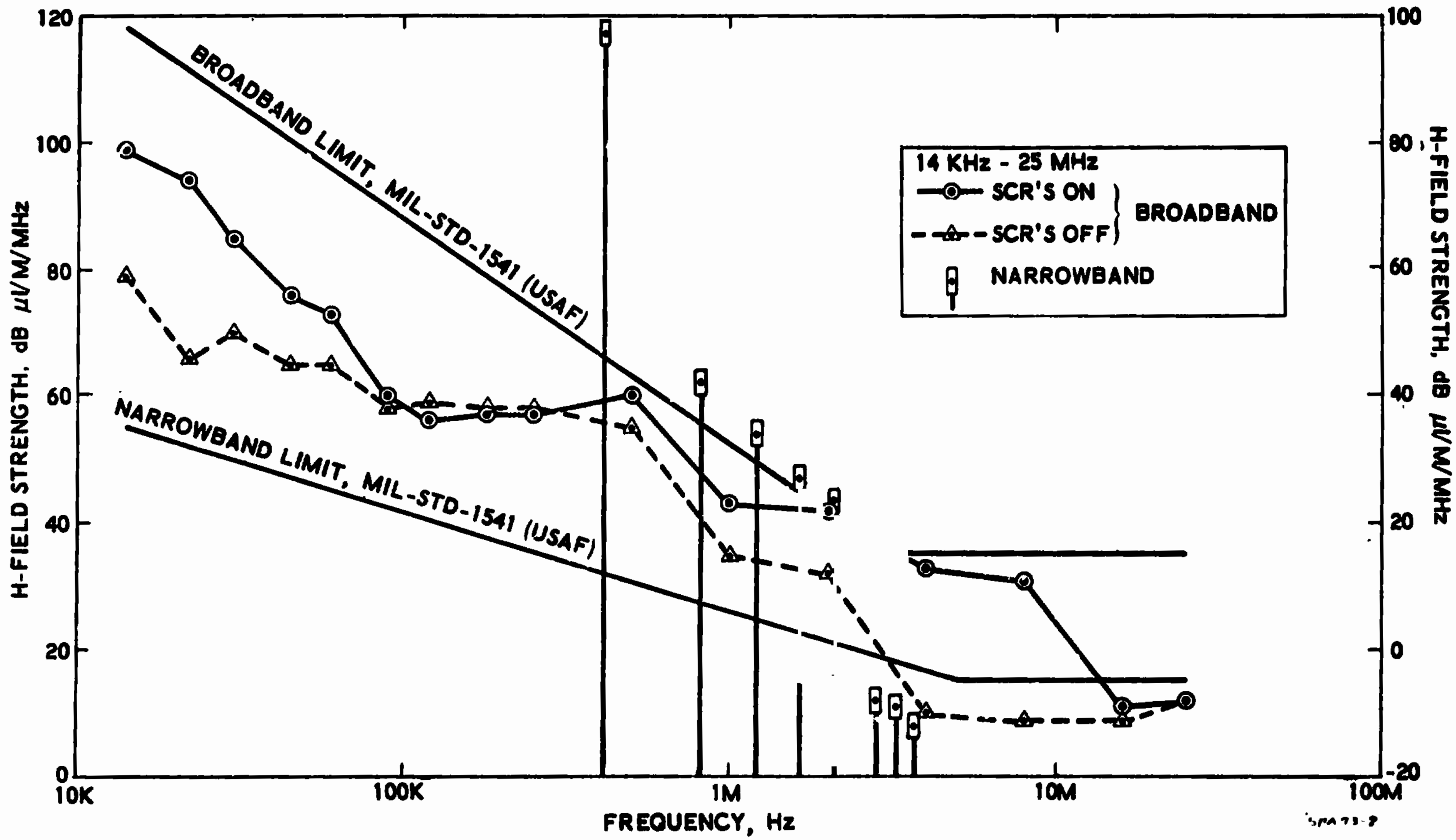


Figure 45. Cycle-Dyne SCR Power Supply and 3.5 KW Induction Heater (H-Field Narrowband and Broadband Radiated Emissions)

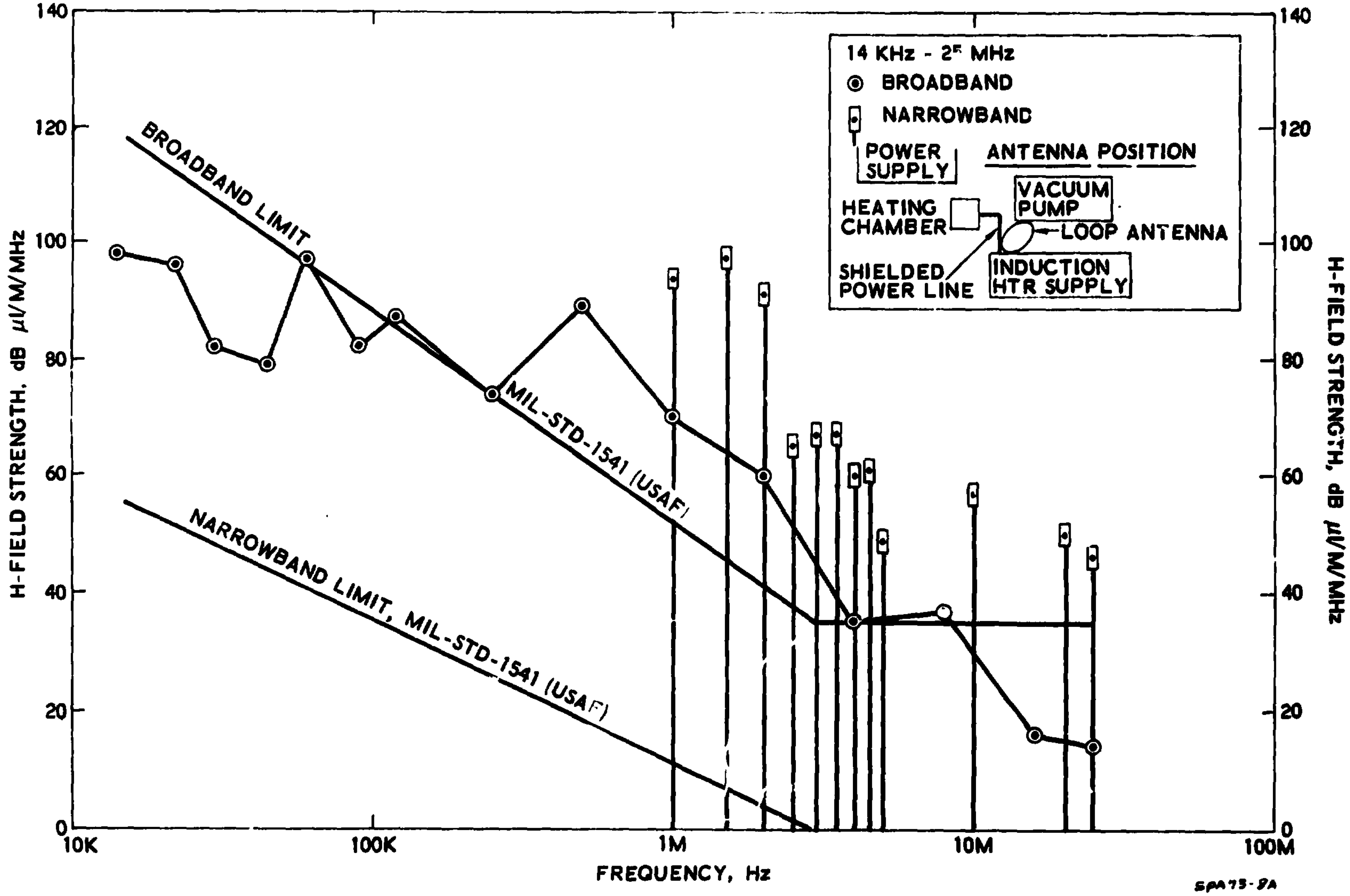


Figure 46. Helmholtz Type Electron Beam Power Supply
(H-Field Narrowband and Broadband Radiated Emissions - Induction HTR#2)

and an approximate penetration loss of 8 dB per skin depth, an overall attenuation of 100 to 110 dB can be estimated for a 1 GHz signal. A 1-kW (+60 dBm) heater, without additional external shielding, may therefore be considered to be capable of radiating a power density of approximately -50 dBm/m^2 at a one-meter distance.

A low noise receiver, typical of the ones used for S-band spacecraft communications, may employ a sensitivity of -110 dBm/MHz. In the absence of any specific information about the Space Shuttle antennas, if one assumes omnidirectional gain of unity for the backlobes, a 1-m^2 capture area, and a separation distance of 10 meters between antenna and heater, a path loss of 170 dB would seem to be a reasonable minimum requirement. Of that value, approximately 130 dB may be assigned to the RF cavity shielding and to path loss, but at least another 40 dB of loss will be required of the external housing of the heater. In addition, it may well become necessary to restrict the range of operation of the microwave heater in order to preclude any possibility of interference with the on-board communication gear.

5.2.1.2 Transient Radiated Interference

One of the major sources of transient radiated interference in the SPA payload my be the flashtube assembly used to pump the pulsed laser. Figures 47 and 48 illustrate the levels of transient radiation measured at a 1-meter distance from an unshielded laser head assembly. As may be seen from the graphical data, the levels of broadband radiated interference exceed the allowed E-field values of MIL-STD-461A, Space Shuttle Amendment, by from 40 to 60 dB over the entire range from 14 kHz to 20 MHz. The radiated H-field limits are again specified only to an upper frequency of 50 kHz, but are exceeded even within that range by 40 to 50 dB. To reduce these levels of transient radiation, the choice of available units may well be narrowed down to those utilizing well grounded metallic enclosures for the flashtube assembly or those capable of being modified to such a configuration.

5.2.2 Potential Susceptibility Modes

To evaluate the shielding requirements for electronic circuitry representative of potential SPA equipments, data is required on the average susceptibility level of such circuitry and also on the potential interference pickup in any interfacing harness path. Actual experimental

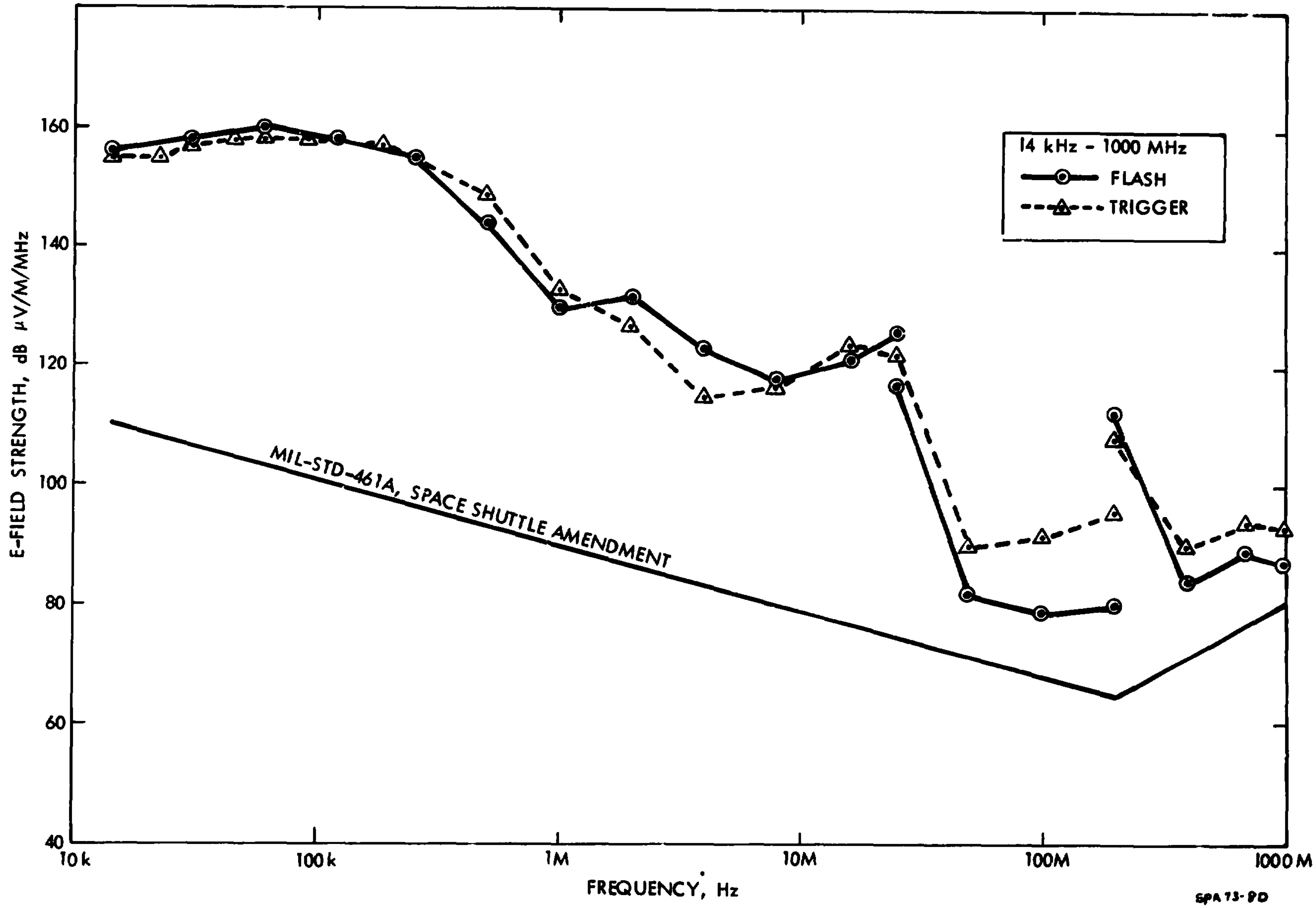


Figure 47. Eight-Turn Flashtube (4 kV) (H-Field Broadband Radiated Emissions)

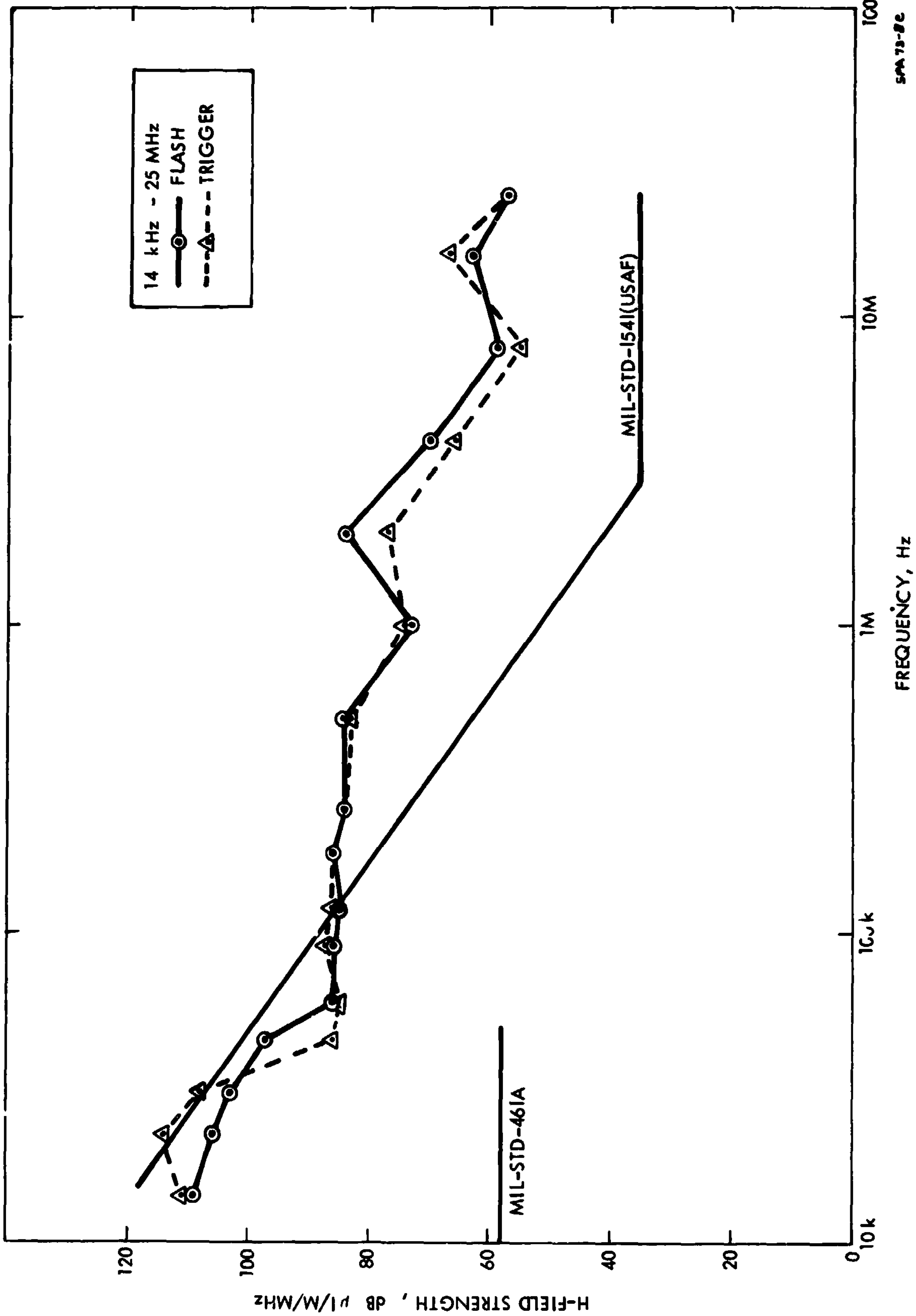


Figure 48. Eight-Turn Flashtube (4 kV) (E-Field Broadband Radiated Emissions)

determination of such data at the equipment level is impractical at this point due to the difficulty of generating the expected environment other than with the source equipment itself (i.e. induction heater coils, flashtubes, modified microwave ovens).

5.2.2.1 Circuit Cards

The selected approach towards determining the minimum shielding requirements for electronic circuitry has therefore been based upon the generic characteristics of commonly employed circuit layouts. As an example, several studies in the literature have attempted to assess the susceptibility of linear and digital integrated circuits at the circuit board level. Comparing these threshold values against the previously obtained data on the potentially prominent emission sources, it can be concluded that linear circuits (operational amplifiers, A/D converters, differential amplifiers, buffer circuits, etc.) can be affected at the circuit board level at distances of 1 meter or more from the major SPA interference sources. Digital circuits are generally more tolerant to radiated interference, but this tolerance is offset by their increased bandwidth and broadband response characteristics. These conclusions have been derived from the data shown in Figures 49 and 50, and indicate that, as a baseline, consideration should be given towards repackaging SPA equipment into RF-tight enclosures. Consideration should also be given to packaging critical analog circuitry in magnetically shielded modules.

5.2.2.2 Fuel Cell Voltage Modulation

One of the major weaknesses of standard EMC specifications is that the allowed levels of conducted interference are specified in terms of AC current, while the test levels for susceptibility are specified in terms of voltage. This oversight of the source impedance coupling between the two factors can lead to higher than expected voltage excursions in the fuel cell outputs. The chief reason for this phenomena is that the impedance of a fuel cell varies as both a function of frequency as well as a function of DC load current. It is therefore insufficient to specify the 28 V ripple independent of this loading. The 400 Hz inverters can be expected to draw a sinusoidal current from the fuel cells. Since the inverter, or inverters, generate single-phase power, the inverter input current modulates the output voltage of the fuel cell, and a variable conducted noise voltage is introduced into units operating directionally from the 28 V power.

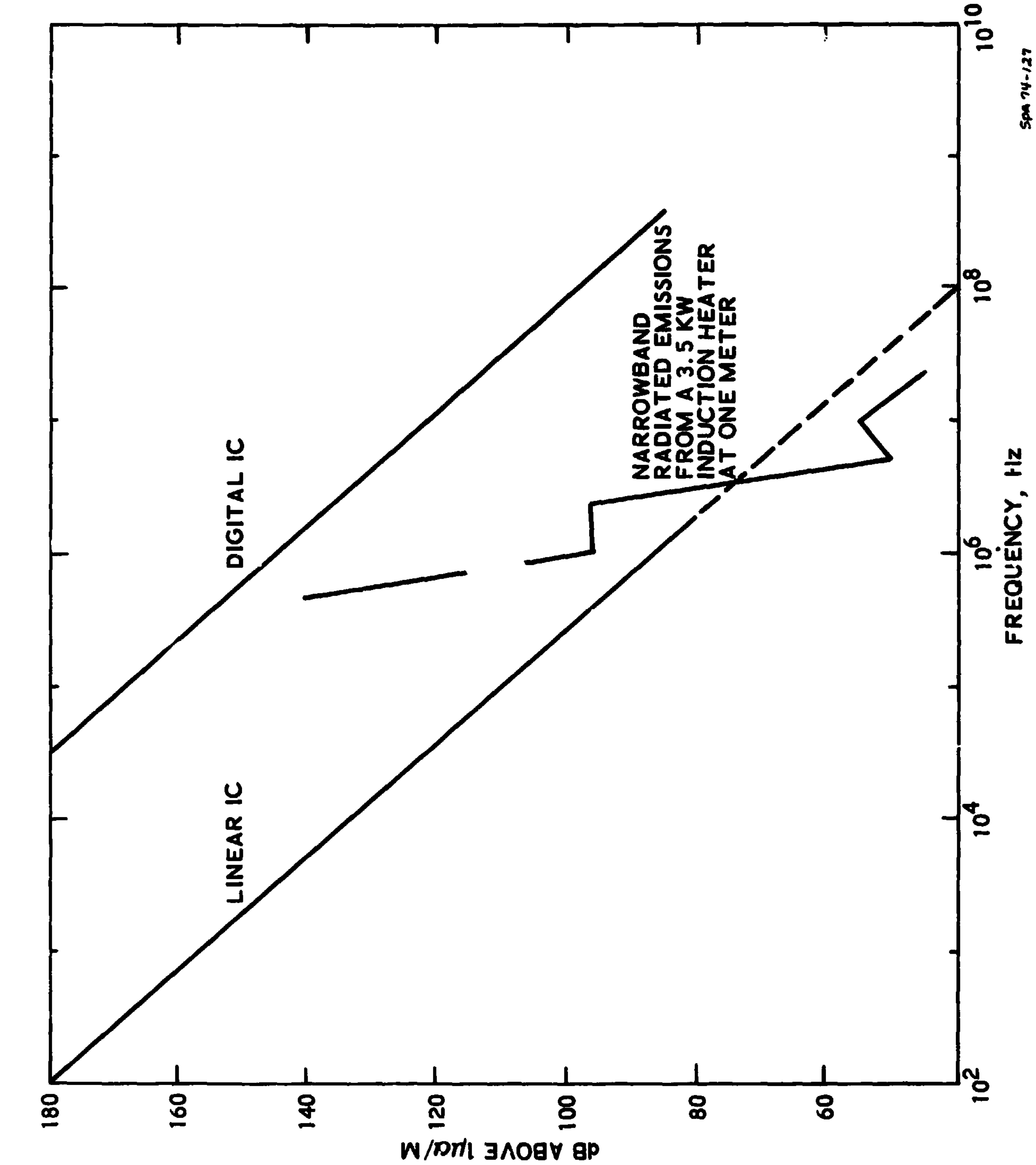


Figure 49. IC Susceptibility To H-Fields

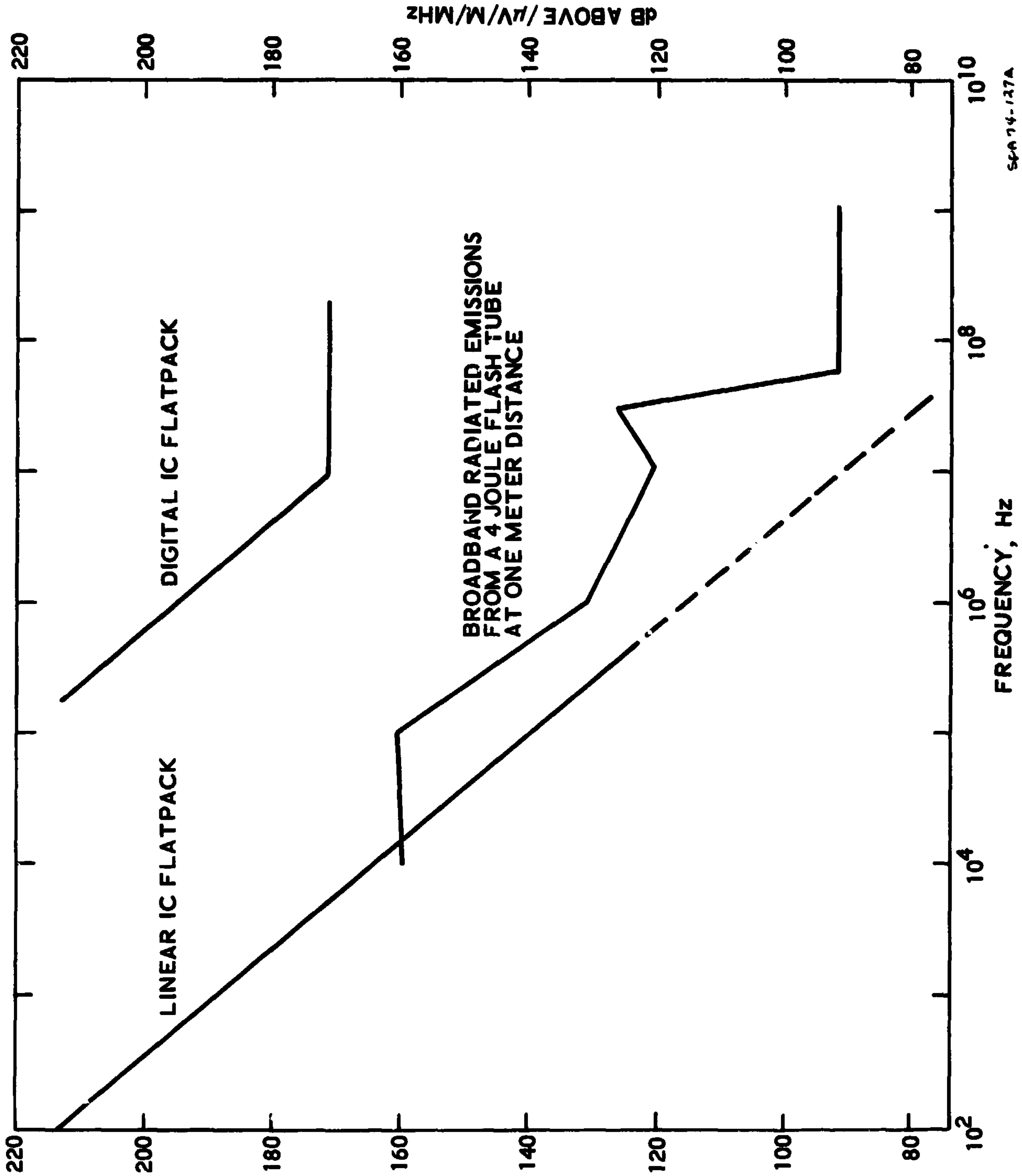


Figure 50. IC Susceptibility To E-Fields

An example of the range of impedances which may be encountered in a fuel cell is shown in Figure 51. The data was reported to have been obtained on a 28-cell Allis-Chalmers 200 watt, hydrogen-oxygen module and has been included in this report principally to shown the range of impedances one could expect to encounter. It is certainly recommended that similar data be obtained on potential Spacelab fuel cell packages and the levels of conducted interference specified for the equipment to be reexamined before final publication.

5.2.3 Computer EMC Analysis

In view of the lack of data about the final Spacelab configuration and its operating characteristics a realistic assessment of the potential compatibility of SPA payloads and Spacelab interfaces has not been deemed to be feasible at this writing. This effort can proceed once a candidate configuration and payload have been selected, where it will require the assumed geometry of the configuration to be specified. Models suitable for entry into the SEMCAP computer program, have been generated based on the emission data outlined in section 5.2.1, and the susceptibility criteria described in section 5.2.2 above. Models are also available for both conducted as well as radiated levels of allowed emissions per MIL-STD-461A, Space Shuttle Amendment, and initial estimates have been prepared for the responses of typical command, telemetry and control circuits.

The data still to be determined before any reasonable estimate for EMC interactions can be obtained rests principally in the geometrical terms required to specify the interaction distances and harness routes, and the sensitivity and bandwidth characteristics of typical Spacelab/SPA interfaces.

5.2.4 EMI Environmental Estimates

The principal cause for special EMC concern uncovered during the course of this study has been the induction furnace payload. Most other sources of potential interference, such as the unshielded laser head or the microwave oven, appear to be amenable to control via normal EMC suppression techniques. But operation of the induction heater and excitation circuitry within the rather close confines of Spacelab will demand a considerable effort in terms of noise suppression and immunization techniques, in terms of test simulation requirements, and in preventive EMC design. Particular attention will have

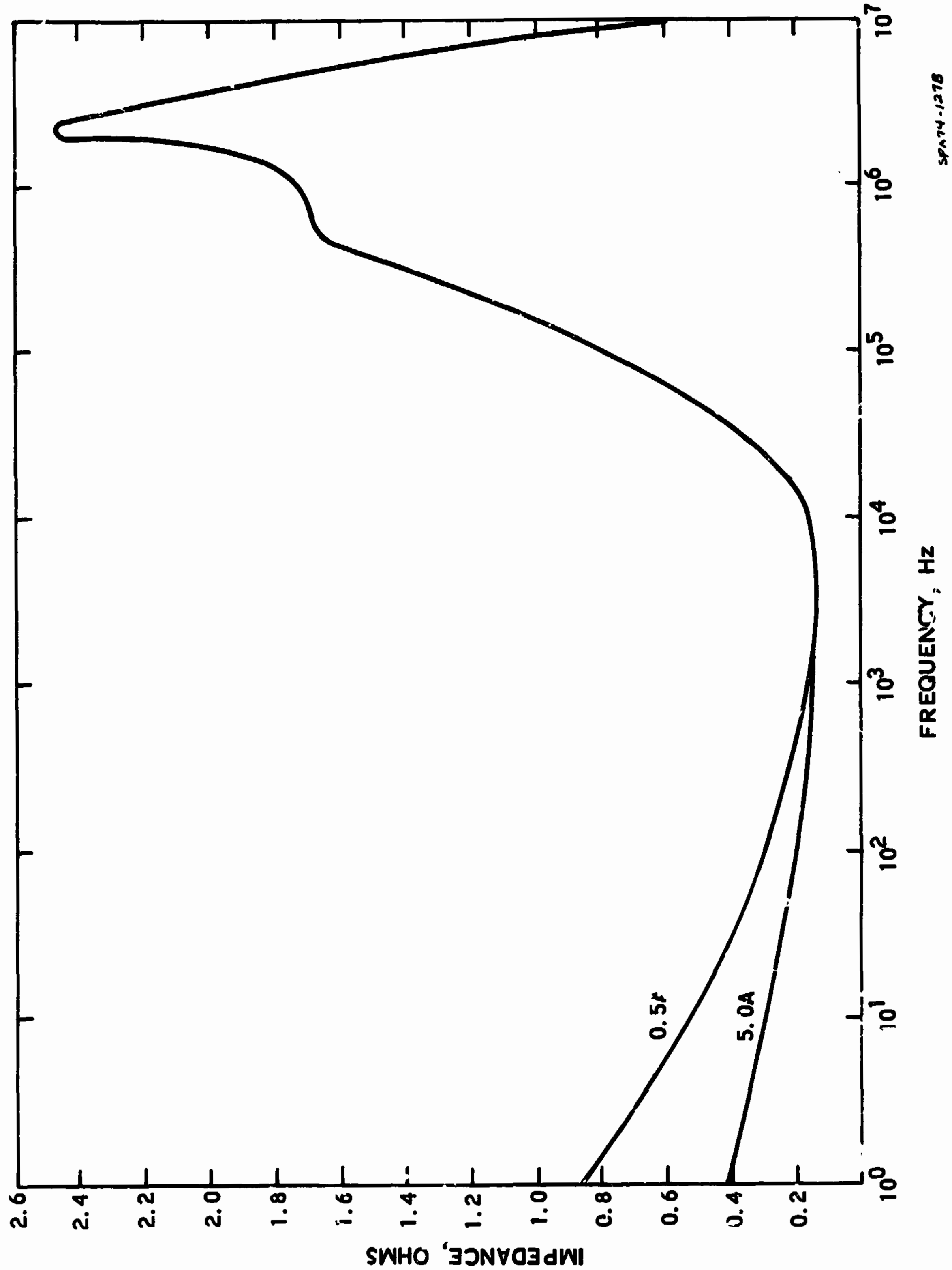


Figure 51. Small Signal Impedance of a 28 Cell, 200W Hydrogen-Oxygen Module

to be paid to the mechanical layout of harnesses, the orientation of the coil itself, the grounding configuration of associated circuitry and the signal transmission techniques to be employed.

At this time, it appears that the most significant shortcoming of the Space Shuttle Amendment to MIL-STD-461A lies in the area of magnetic field susceptibility requirements for the Spacelab and associated equipment. Any shortcomings in the noise immunity of the as yet untested portions of the SPA candidate payloads or in their interference suppression characteristics are of course also of concern but do not appear to carry the same potential for serious interference with the host vehicle.

5.3 AVAILABLE EMI DATA FOR COMMERCIAL EQUIPMENT

There exists an almost total lack of available information about the EMC characteristics of the commercial equipment surveyed for SPA. Even if this information were available, it is doubtful that it would be of direct value due to the evident necessity of modifying that equipment thermal and electrical interfaces with the Spacelab. In addition, several changes would need to be made in the test methods used to derive such data. As an example, most conducted interference measurements are performed by utilizing a 1-ohm or similar low impedance source. For SPA, the source impedance for higher power loads should be simulated by a current limited source, a condition imposed by the 400-Hz or 1600-Hz inverters. Similarly, conducted interference and susceptibility characteristics of the candidate equipments can be expected to change significantly from those measured under 60-Hz operation.

Summarizing, EMC characteristics for candidate SPA equipments are lacking, but this drawback is tempered by the fact that significant variations in such data could be expected as a result of mechanical equipment redesigns and power supply modifications. A test effort to obtain such data will become practical only at a time when the candidate payload configurations have been more closely defined in specific detail for each equipment.

5.4 SPACELAB AND SHUTTLE VEHICLE EMC

The findings outlined so far have indicated that the wide variety of potential SPA configurations are not very amenable to a generalized

specification approach. Nothing that has been determined up to this point precludes the previously outlined approach to use of preliminary computer-assisted EMC assessments for SPA missions, but the potential range of serious interactions of the payload with the ferry vehicle requires a greater degree of definition of the EMC characteristics of at least the Spacelab.

5.4.1 General EMC Specification Approach

Any assessment of a general EMC specification approach to SPA payload configurations shows that the degree of extra protection required to encompass all candidate components would impose significant financial impacts. This impact may be unavoidable in the case of the standard Spacelab mission-independent constituents, such as the data handling and communications gear, but appears to be avoidable for selected payload configurations. To accomplish such an objective, it appears that a dual specification approach may be appropriate to SPA. In that approach a generally more severe EMC specification would be developed for the Spacelab equipments to encompass the envelope of the worst expected environment resulting from all potential payloads. This approach carries with it the advantage of reducing potential downtime for resolution of payload integration problems. Its disadvantage may be a higher initial cost resulting from a need to upgrade already space qualified equipments.

5.4.2 Mission Specific Analytical Approach

This mission specific analytical approach carries with it the advantage that once the EMC characteristics of the Spacelab have been established, the only modifications required for a specific mission analysis are the description of the payload. Overdesign is avoided because only one particular configuration is evaluated at a time, and otherwise substandard performance characteristics may be found to be still acceptable in a specific application. In addition, any Spacelab related equipment modifications may be inserted into the computer model at the time of its implementation, without requiring a general upgrading of all the remaining payloads.

5.4.3 Specification Development Prerequisites

Before either of the above outlined approaches reaches the point of modifying any existing specification limits, further EMC data will have to

become available about the selected configuration of Spacelab and its command and data handling characteristics. Pertinent points include the secondary power distribution and grounding philosophy, the acceptable range of source and load impedances and the levels of tolerable interference on interfacing circuits. To a certain degree, these parameters may already be estimated if it can be assumed that the level of technology and circuit sophistication is to be based upon generally existing commercial equipment. As a minimum, it is felt that any pertinent data derived from the experience gained on Skylab be factored into the SPA EMC criteria selection process.

5.5 TEST RECOMMENDATIONS

The present phase of the SPA EMC assessment has uncovered the almost total lack of EMC test data on candidate payload equipments. It has also shown that a good portion of such data, would it have been available, would have been difficult to utilize in terms of the proposed electrical power subsystem configuration and the demands imposed by the thermal environment of the Spacelab. To circumvent these conditions, it is recommended that a modified EMC test program be initiated along the lines of an exploratory engineering investigation, similar in nature to the already accomplished tests on induction heaters and flashtubes.

5.5.1 Conducted Interference and Susceptibility

Where power supplies on candidate SPA equipments have been designed to operate over the 60- to 400-Hz frequency range, engineering evaluation tests would provide a useful indication into the equipments potential behavior on Spacelab. Use of simulated current limited power supply should give important information about the expected transient behavior of such components and the resultant information from susceptibility testing would provide some feedback for the design implementation of the AC power subsystem.

5.5.2 Radiated Interference and Susceptibility

Recent simulated arc-discharge tests at TRW in support of another space program have shown that a considerable amount of data on potentially erratic circuit behavior can be obtained in a relatively short time. Such tests serve as qualitative indicators of the adequacy of the incorporated EMC design features and serve to identify the weaker links in the signal or data processing chains. By such means a considerable amount of test time is

saved, and an immediate follow-on effort becomes feasible to characterize the properties of potential trouble spots at the circuit level. Such a test also provides an excellent indication about the adequacy and relative noise immunity of any associated interface circuitry. The test also provides a reasonable measure of protection against causing permanent damage to the equipment due to the shortness of the radiated RF pulses. Such a test could serve to simulate any of a number of potential transients the equipment might encounter in actual use and should therefore provide valuable insight into the relative noise immunity of candidate SPA equipments.

Radiated interference measurements on equipment configured for commercial use on the ground can best be employed as diagnostics. Primary contributors may thereby be identified and an estimate can then be established on the relative amount of RF shielding to be required from the equipment enclosure when modified for SPA use.

5.5.3 Scope of Test Effort

Considering the intent of the investigations to be for purposes of gathering engineering information, it is reasonable to assume that the actual test effort per equipment can be held to two weeks of test time or less. These estimates are based upon the availability of semi-automated test equipment and a limited amount of engineering investigation into unexpected equipment behavior. TRW has also performed similar investigations in the past and has the personnel, facilities and equipment needed to carry through the outlined investigations.

5.6 CONCLUSIONS

The intent and direction of this study was to identify the most prominent problem factors that could influence tradeoff studies and that would lead to solutions of problems related to matching SPA payload needs to Spacelab/Shuttle capabilities. The initial efforts expended during the EMC Subsystem interface study clearly fulfilled the early expectations that evaluation of EMC characteristics would be hampered by the almost total lack of such data for the equipment items under consideration.

A two-pronged effort was undertaken to determine the EMC impact to employing commercial equipment: (a) in-house test program and (b) a literature review.

The results of these aspects of the study have been presented within this section of this report. Tasks that would provide further identification of equipment performance criteria as effected by the EMC interface include a consortium of modeling and susceptibility analysis that culminates from a test matrix.

It is clear that from the studies presently completed in the EMC Subsystem task that the continuing EMC effort for SPA should be the mission specific analytical approach for purposes of modeling the system for EMC analyses.

6. REFERENCES

Power and Distribution Subsystem

1. Spacelab System Specification (Level II), Issue 3, Revision 2, Contract Document 8, European Space Research Organization, 15 October 1973.
2. Fuel Cell Powerplant Procurement Specification, MC 464-0115, Space Division, North American Rockwell Corporation, May 10, 1973.
3. Sortie Lab Phase B Definition Study, Autonomous Electrical Power System Design Reference Model, S&E-ASTR-SE, Prepared by Space Support Division, Sperry Rand Corporation, July 23, 1973.
4. MDC E0391 Space Shuttle Data-Electrical Power, McDonnell Douglas Report, 30 June 1971.
5. Space Shuttle and Spacelab Discussions, Volume D, Electrical Power and Distribution JSC08500, NASA-JSC, October 11 and 12, 1973.
6. A. Krausz, Final Report-Space Vehicle Electrical Power Processing, Distribution and Control Study, Volume II - Technical Report, TRW Systems Group, June 1972.
7. Marshall Space Flight Center, Sortie Lab Task Team, Program Development, "Sortie Lab User's Guide," April 1973, (Interim Issue based on U. S. option).

Thermal Control Subsystem

8. J. E. Eninger and D. K. Edwards, "User's Manual for the TRW Multwick Program," Contract No. NA5-11476, October 1973.
9. NASA CR-61363, "Phase Change Materials Handbook," September 1971.
10. TRW Sales No. 22886.002, "Space Processing Applications Payload Equipment Study, Study Plan," July 21, 1973.

EMC Subsystem

11. R. H. Kelkenberg, "The Effect of Fuel Cell Internal Impedance on Power Supply Noise," 1970 IEEE EMC Symposium Record, July 1970.